Geological evaluation of subsurface features near Ithaca, NY: interpretations of seismic reflection profiles collected by the petroleum industry

Basis for analysis: data “leased” to Cornell
through ACSF-AVF project of Pritchard, McComas, and McLaskey

Report to ESH leadership, Cornell University

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Note: Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

Executive Summary

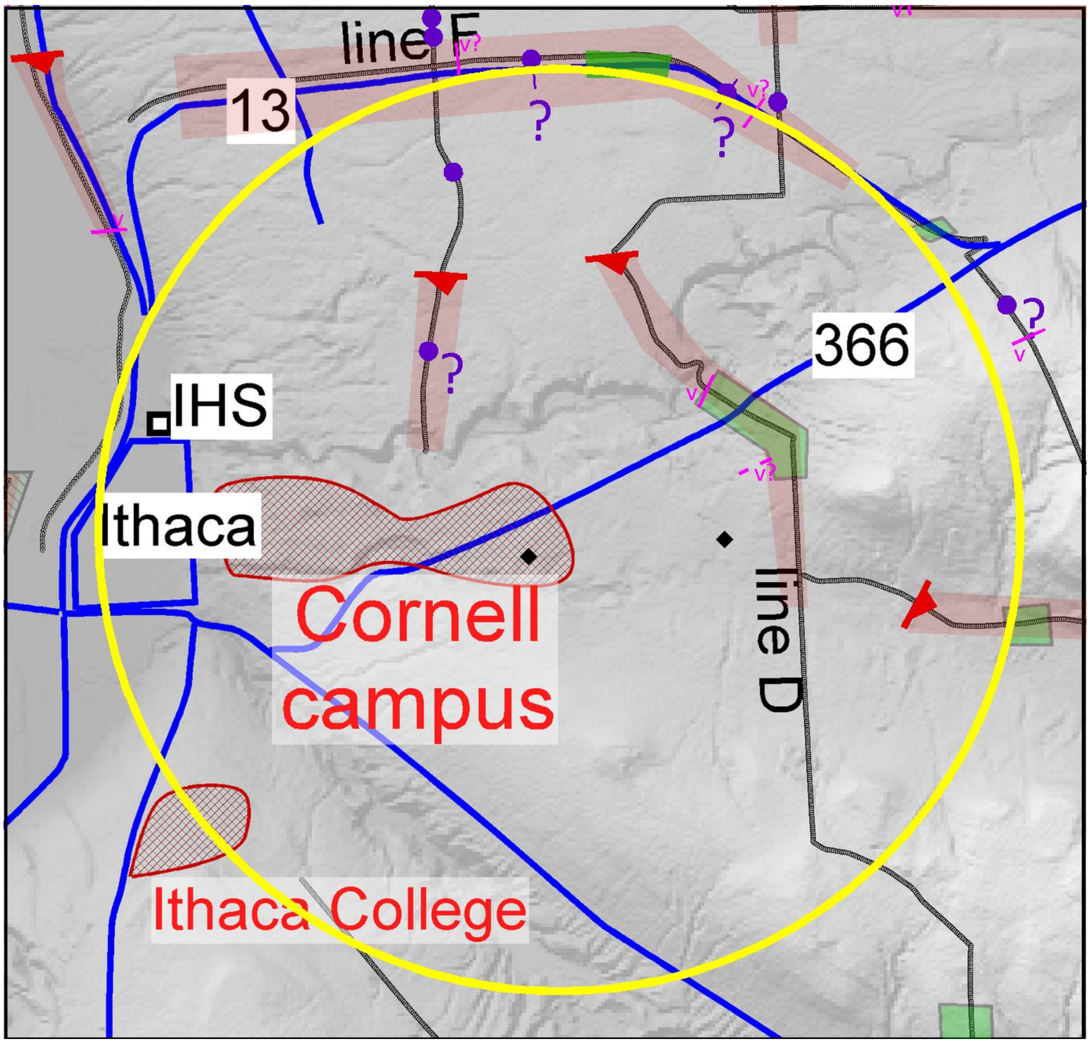
To provide background geological information with which to assess some of the technical and environmental risks of a Cornell Earth Source Heat (ESH) project in Ithaca, NY, this report describes the geological features below Tompkins and easternmost Chemung counties that are revealed by approximately 150 km (94 miles) of 2D hydrocarbon-industry seismic reflection profiles. Details of subsurface features near the Cornell campus are presented on maps, and also described. Such data were not previously available in any publicly available reports, and therefore the analysis presented is a major step forward in documentation of subsurface features near Cornell.

The vertical distribution of sedimentary rocks known from deep hydrocarbon boreholes was used as the basis for the approximate sedimentary unit identification of packages of seismic reflections to a depth of about 3 km (10,000 ft). The lower limit of sedimentary rocks, which overlie a crystalline basement, can be identified readily in only a minority of the seismic profiles; in most of the data, there is a large uncertainty on position of the basement contact. Sedimentary units with possible interest as geothermal reservoirs are expected within the lowest 300-600 m (1000 to 2000 ft) of sedimentary rocks near Cornell. These data allow tentative identification of a unit of sedimentary rocks with favorable reservoir potential immediately overlying the basement in paleovalleys near campus.

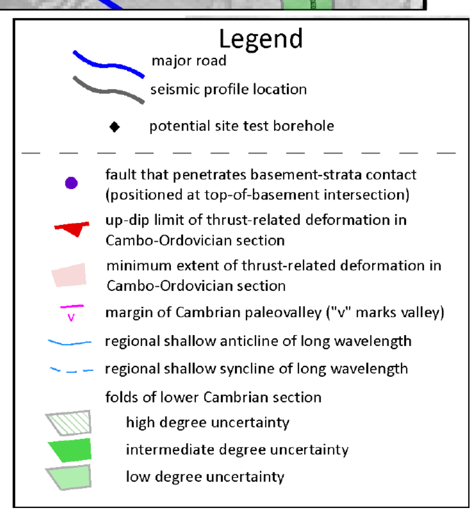
Disruptions to the positions or continuities of these reflective sedimentary rock units are identified as either folds, which are smooth undulatory waveforms of the rocks, or faults, which are breaks in the units. Two classes of faults, one sub-vertical and one sub-horizontal (i.e., thrusts) are differentiated such that their different roles in technical and environmental risk can be individually evaluated. The seismic profiles reveal five categories of structural deformation, two of which were not expected based on publicly available reports for Tompkins and neighboring counties.

Among the three expected categories of structural deformation, folds of the uppermost sedimentary layers are widespread; these should impact an ESH project only by making predictions of depths to horizons of interest slightly more uncertain. Folds and thrusts within the Syracuse and Vernon Formations are highly likely to occur under the Cornell campus region and plausible ESH project sites, in a depth range of 750-1200 m (2500-4000 ft). These widespread features are not shown in the executive summary illustration, yet they are detailed in the report. Standard practices exist in central New York for drilling through and isolating this interval of deformed, weak rocks.

The seismic reflection profiles reveal that the third expected category, sub-vertical faults known by the hydrocarbon industry as “Trenton-Black River” (TBR) structures, occurs in some sectors of Tompkins County. A Trenton-Black River fault cluster is not expected near the Cornell campus (see summary figure). An uncertain individual TBR-type fault is located about 1.4 km (0.9 mi), and a more reliable single fault about 3.4 km (2.1 miles), north of the Palm Drive area. The first unexpected category of structures is a widespread set of sub-horizontal thrust faults within the Cambrian and Ordovician sedimentary rocks, in an interval of rocks predicted from boreholes to be about 350 m (1150 ft) thick at Cornell’s campus. The near-Cornell industry-quality seismic reflection profiles reveal thrust faults in these sedimentary units (see summary figure). A seismic depth model with high uncertainty implies that these thrusts may be as shallow as 2.1 km (6900 ft) or as deep as 3.0 km (10,000 ft) near the east end of campus. Because of their sub-horizontal disposition, these disruptions may have more relevance to analyzing reservoir potential than to seismic hazard analysis.



The second unexpected category of structures is of greater uncertainty than any of the other features described here. Within Tompkins County, there are a small number of fold-forms in the deepest well-imaged sedimentary units. There is a significant degree of uncertainty that some or all of these fold-forms are physically real parts of the rocks. Conventional geological wisdom suggests that these undulations may be associated with faults that are not imaged by the seismic reflection data. Hypothetically, either of two markedly different types of faults could be related to deep folds: near-vertical faults (like the TBR faults)



that offset rocks in the basement, or sub-horizontal thrust faults within the poorly imaged deeper sedimentary rocks or at the sedimentary rock-basement contact.

I recommend that additional modeling and analyses of the seismic reflection data be considered, in efforts to reduce the uncertainty on the fold-forms near the base of the sedimentary rocks, to improve estimates of the depth to reflectors, and to learn whether more useful information about the crystalline basement can be extracted. This study, supplemented by the Vibroseis survey collected in 2018 by Professor Brown and students, has illuminated relatively well the nature of the sedimentary rocks near the eastern edge of the Cornell campus development. Because sub-vertical faults projecting down toward the basement are not revealed close to campus, it is my opinion that investments in future geophysical studies should focus on extracting information about the crystalline basement rather than about the sedimentary rocks. Perhaps the best designs for further geophysical studies will involve instrumentation within a pilot borehole that complements instrument deployments across the land surface.

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1. Scope of Analysis

Seismic reflection profiles use sound waves to find interfaces between rocks units of contrasting density and velocity in the subsurface. Because the data are collected by inducing vibrations at Earth's surface and recording reflections of the sound pulses, the method images well horizontal or sub-horizontal boundaries, but does not image near-vertical or vertical boundaries. Hence this report focuses on information gleaned from the spatial variations in depths to the widespread, sub-horizontal sedimentary rock of Tompkins County, which are well resolved. The data were collected in profiles along many of the roads, and data are absent for the areas between roads. An exception exists where Cornell's geophysical team collected seismic reflection profiles in 2018.

The vertical unit on seismic reflection profiles is "two-way travel time," i.e., the time it takes sound waves to go from the surface of the earth to reflecting interface and return. This metric can be converted to a linear depth-below-surface unit by use of a velocity to depth-conversion model, but this step introduces a relatively large degree of uncertainty. To avoid introduction of this uncertainty, most results reported herein are presented as two-way travel time (TWTT).

Seven categories of structural features which interrupt or alter the simple, planar extent of the reflective sedimentary rocks are described, and their locations presented within Tompkins County area. Closer attention is focused on an 8-km (5 mile) diameter region surrounding Cornell University's eastern campus region.

Borehole data reveal the nature of the rocks whose interfaces are imaged by the seismic profiles. The rock types and their sonic wave velocity are referenced in this report based on borehole data. An assessment of the uncertainty on predicted depths to specific rock interfaces at locations on the east side of the Cornell campus compares extrapolations from boreholes spaced many kilometers from Cornell, to depths modeled by depth-conversion of the seismic reflection data.

This report does not attempt to relate the seismic reflection interpretation to the gravity and magnetics studies carried out by Dr. Frank Horowitz, or to the analyses of data from the temporary local seismic network by either Professors Katie Keranen or Larry Brown. The comparison between these interpretations and the analysis of the Vibroseis seismic reflection survey carried out by Professor Larry Brown will be provided in Brown's report. This report does not make any recommendations as to the feasibility of ESH development and carries out no risk assessment as the author is not qualified to do so.

2. Data sources and limitations

As a part of exploration for hydrocarbon resources in central and southern New York during the time interval 1950-2010, various seismic reflection profiles were obtained by oil and gas companies and numerous deep exploratory boreholes were drilled and tested. Whereas a state agency maintains public records of the exploration borehole data, there is no regulatory requirement that the costly seismic reflection profiles be placed in the public domain. Instead, these data sets are commonly sold to a data brokerage firm when a company ceases to consider a region to be of business interest. For the central New York region, Seismic Exchange, Inc. (SEI), a data broker, owns much of the seismic data.

Through a lease agreement for 40 years, PI Pritchard obtained from SEI access to approximately 150 km (94 miles) of reflection seismic data as part of an Atkinson Center Academic Venture fund award to (among other things) understand the characteristics of faults and fractures in the subsurface using seismic data for use in geothermal development. The majority of the data had been delivered to SEI in a format that was not readily accessible to SEI's potential clients, hence SEI agreed to a steep academic discount to Cornell for lease of the information, on the condition that we return the data to SEI in a more useful format for their future lease use. The majority of the processing (and all of the processing within the area of interest around Ithaca) was completed by Star Geophysics, who provided migrated, stacked, time-sections. Data on two lines from the 1980s that extend beyond Ithaca were processed by a Cornell employee (Daniel May) who compared his analysis to that undertaken by Star Geophysics in the area of overlapping analysis.

SEI's business depends on repeated leasing of their data, and hence they restrict the extent to which the seismic reflection profiles can be shown in public forums or in printed/published forms. Cornell's interpretations of the data can be shared freely. SEI has approved the posting of this report on eCommons, a Cornell library archive service, but requires that future derivative reports or presentations must be approved by them.

Eight seismic reflection profiles were available for study (Fig. 1). Two lines that together provide full coverage over a north-south distance of approximately 64 km (Fig. 1B, left gray line), and pass through the western part of the City of Ithaca, are 1980's vintage data and 1980's data processing. While invaluable to this project, seismic profiles of that era lacked sufficient quality to identify the small faults of interest for a new wave of gas exploration in the 2000's. Hence higher resolution data were collected in the 2000's. The other six reflection profiles reported here (Fig. 1, all other gray lines) were collected in 2007 and processed by Star Geophysics in 2018-2019. These form a grid of approximately orthogonal profiles that spans roughly 13 km north-south, and 10 km east-west, essentially bounding the north, east and south sides of the City of Ithaca. The Cornell vibroseis profiles (reported separately by Larry Brown and Daniel May), collected in 2018, are immediately adjacent to one of the industry seismic lines, and extend the information reported here into Cornell-owned land.

The mandated reporting of borehole data is regulated by the New York State Division of Environmental Conservation. The data are archived in the Empire State Organized Geological Information System (ESOGIS), which is maintained by a geological unit within the New York State Museum. Although much of the ESOGIS system is subscription based, full access is given to university geological research groups. Although many thousands of boreholes were drilled in the Southern Tier for hydrocarbon and salt exploration, only five deep wells (>1 km [3280 ft]) exist within a 24 km [15 mile] radius of the Cornell Campus (Fig. 1). Of those, only one penetrates to Precambrian basement underlying the sedimentary section (Shepard-1, near Danby).

A B

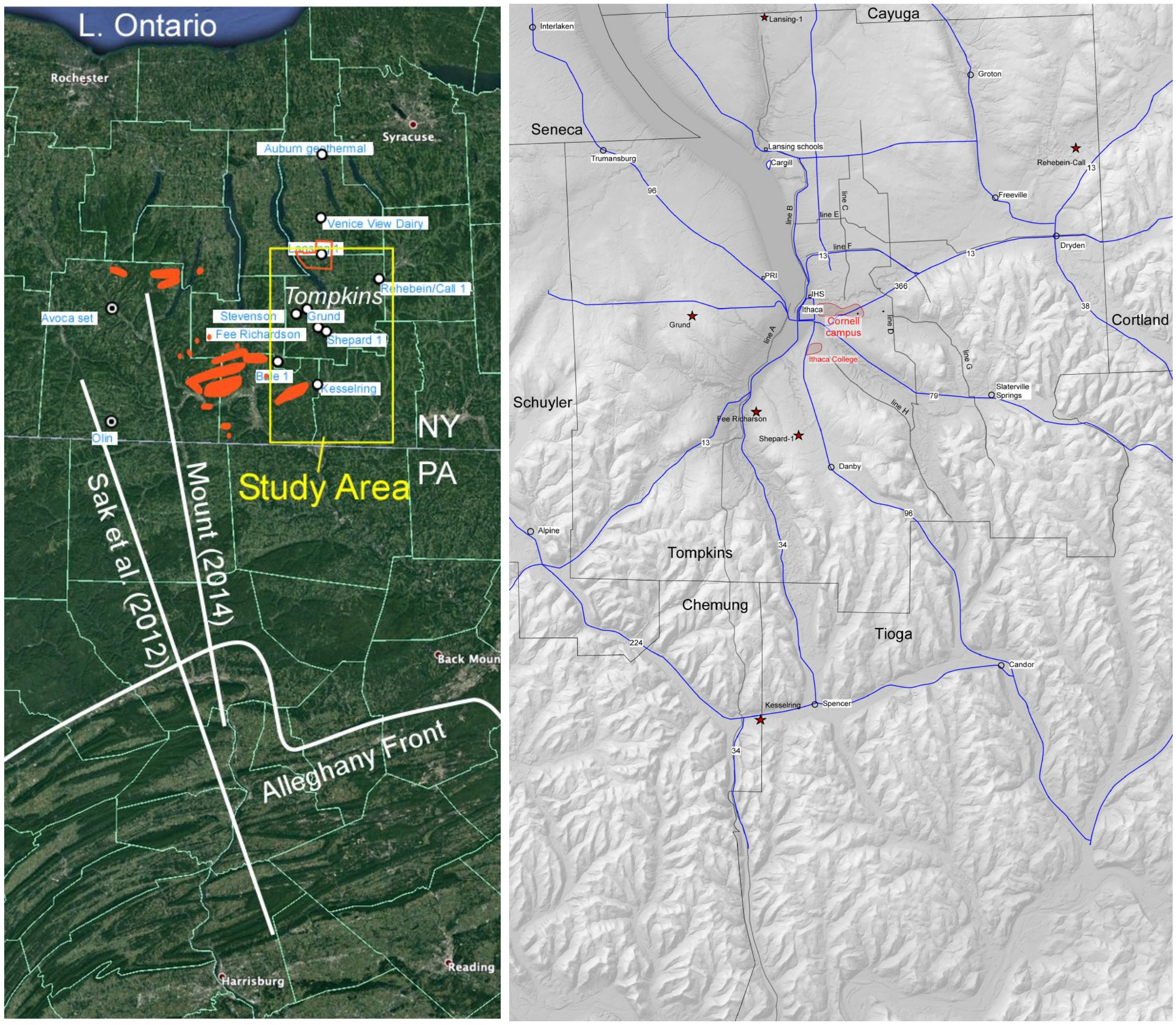


Figure 1. A). Study area (yellow box) relative to counties of central New York state and key boreholes (blue lettering). Locations of reference subsurface interpretations are marked: seismic reflection interpretations from Tamulonis et al. (2011) in orange polygon north of Tompkins County; structural cross sections from Sak et al. (2012) and Mount (2014) indicated by white lines connecting south central New York to Pennsylvania's Appalachian Mountains. Orange polygons mark Trenton-Black River fault-controlled gas fields. B) Within yellow rectangle of "A", locations of available industry seismic reflection lines A-H (gray lines) (Seismic Exchange, Inc., data), relative to county boundaries (black), major roads (blue), and boreholes (stars) whose records were utilized in interpretation of the seismic data. Cornell University and Ithaca College main campuses are shown with red cross hatch.

3. Expectations for structural deformation of sedimentary units

Among key attributes for the assessment of geothermal energy extraction potential, for hazards analysis, and for design of reservoir engineering is knowledge of the positions of faults in the subsurface in and around Cornell's campus. Faults are disruptions of rocks; these disruptions occur after a rock is created. For the Ithaca region, which is underlain be rocks that were ductilely deformed and metamorphosed about 1 billion years ago (the crystalline basement) (McLelland et al., 2010) to 360 million years ago (the uppermost consolidated sedimentary rocks), the time span during which brittle deformation may have created faults is long. During that long span, faults of differing mechanical styles may have formed. Furthermore, the interactions of the rocks with fluids over that long span of time may have produced numerous generations of mineral precipitation (e.g., Allaz et al., 2013), which has sealed faults with minerals.

Near Ithaca, layered sedimentary rocks overlie crystalline basement, with the interface located at a depth between 2600 m (8530 ft) (constraint to north) and 3000 m (9800 ft) (constraint to south) below the surface (Al Aswad, 2019).

Deformation structures visible at the surface of the Ithaca region include near-vertical joints (e.g., Engelder, 1985), anticlines and synclines (Wedel, 1932), zones of enhanced fracturing that are interpreted to be near-vertical faults (Jacobi, 2002), small scale layer-parallel shortening across thrust faults (Prucha, 1968) and deformed fossils (Geiser and Engelder, 1983). Published reports on subsurface structures of the Finger Lakes region and south-central New York focus on two classes of structures. First, near-vertical faults control the position of TBR natural gas fields (e.g., Smith, 2006), and hence their locations have been a target for hydrocarbon exploration using seismic reflection profiling and drilling (Fig. 1A, orange blebs). Second, thrust faults (parallel or sub-parallel to the sedimentary rock layers) within the shallow half of the sedimentary rocks (from the Vernon Formation upward), with associated folds, have been described by Sak et al. (2012) and Mount (2014). Subsurface and surface studies are united by Prucha (1968) who studied faulting within and above the salt-bearing units. Prucha (1968) documented that thrust faults, anticlines and synclines persist to at least 610 m depth below Cayuga Lake, in the Cargill salt mine at Portland point.

Saks et al. (2012) and Mount (2014) document the integrated set of thrust faults in the subsurface of northern Pennsylvania (Fig. 1A indicates locations), and project their interpretations north into the Finger Lakes district using sparse subsurface data sets. Figure 2A illustrates the sedimentary rock intervals in Pennsylvania at which the major thrust faults occur. Figure 2B compares the column of rocks 20 miles south of Ithaca, as revealed at the deep Kesselring borehole (Fig. 1A, B), to the Pennsylvania column, and marks the equivalent horizons at which thrusts might be expected. However, the published literature clarifies that one should not expect thrust faults in the lower half of the sedimentary rocks to extend north of the Alleghany Front (Fig. 1A), and certainly not into New York state (Sak et al., 2012; Mount, 2014).

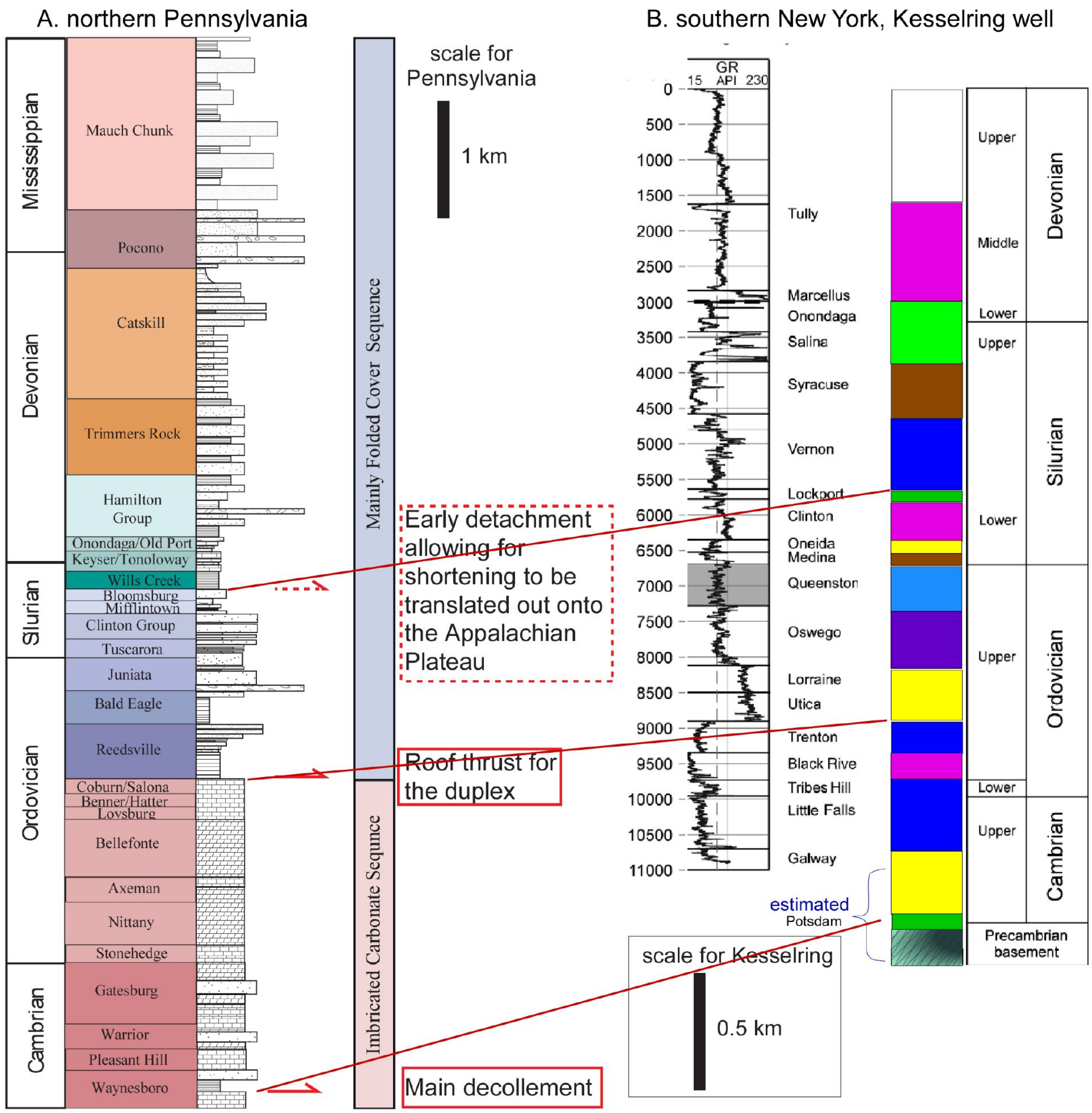


Figure 2. A) Relationship of sedimentary units to the positions of the major bedding-parallel thrust faults (horizontal red arrows), in the strongly deformed Appalachian Mountains of Pennsylvania (from Sak et al., 2012; doi:10.1130/GES00676.1). B) The comparable sedimentary rock column for a borehole 28 km (17 miles) south of Ithaca is displayed at twice the vertical scale as the Pennsylvania column (Tamulonis et al., 2014; doi 10.1190/INT-2013-0009.1), modified based on Al Aswad (2019). Sak et al. (2012) interpret that only the deformation controlled by faults within the Silurian Willis Creek Formation persists into New York state.

Wedel (1932) documented that east-northeast trending anticlines and synclines cross Tompkins County; the wavelength averages 4.3 km. Prucha (1968) documented 76 m of vertical relief across one of these anticlines, a prominent fold visible near Lansing (Fir Tree Anticline). Smith (2006) described the TBR-faults as en echelon, occurring in sublinear trends that persist up to 25 km long, in zones whose full width is usually less than 1 km (Fig. 1A, filled orange polygons). Between adjacent faults, there is usually a downward offset in seismic reflections (Smith, 2006). The sets of faults are interpreted to be transtensional, combining a strike-slip lateral offset that is not readily identified on reflection seismic data, with a small degree of extension, which creates the downward shift of marker horizons. The amounts of vertical displacement on the faults is reported to be minor, on the order of tens of feet, but it is rarely quantified in publications.

4. Methods

4.1. Correlations of sedimentary units to seismic reflections

Interpretation of the sedimentary unit identity of the seismic reflectors initiated with comparison of the Ithaca-area seismic profiles to two publicly available sources of interpreted seismic lines for central NY. For an area near the Tompkins – Cayuga counties boundary (Fig. 1A, unfilled orange polygon), Tamulonis et al. (2011) published a seismic reflection interpretation of eight lithologic units (Vernon Formation to Lorraine Group) expressed within a package of reflectors that corresponds to a 300 ms TWTT interval in the middle of the depth range of interest to this study. Smith et al. (2005) reported the reflection identities of six groups and formations for a long regional seismic profile whose location is specified only as “central New York”. The general changes with increasing depth revealed in those independent analyses, from intervals of high amplitude reflections to moderate or low amplitude, and from simple planar reflections to more complex forms indicative of channel systems, are integrated into the interpretations of the sedimentary unit identities of the Ithaca-area data.

Because of proximity to one of the industry-collected seismic reflection profiles in a sector with very good data quality, the Kesselring borehole (API 31015004430000) (Fig. 1) was adopted as a reference location for identification of the subsurface units within the seismic reflection data set. A sonic velocity log for the Kesselring well permits the vertical series of subsurface formations to be expressed as the modeled two-way travel time (TWTT) at which the tops of major lithological units are anticipated. A comparison of this borehole pseudo-seismic column (Fig. 3C) to the nearby seismic reflection profile (Fig. 3A) enabled the correlation of a small set of seismic reflection patterns to the borehole geology. The rock type changes which most likely create an anomalously strong and laterally persistent seismic reflection are the upper contacts of the Onondaga Formation, Lockport Formation, and Trenton Formation (thick lines, Fig. 3B). Starting from these, a set of key correlations (Fig. 3B, thick and thin lines) was selected because of the widespread occurrence of similar patterns of reflections (tops of Onondaga Formation, Vernon Formation, Lockport Dolomite, Queenston Formation, and Trenton Limestone). Although I established correlations for additional reflectors (Fig. 3D), experience in this seismic profile grid revealed that local variability of the reflection patterns led those other correlations to be less reliable.

These seismic reflection assignments were transferred from the Kesselring borehole region throughout the grid of seismic reflection profiles, by maintaining a consistent position of a formation-identified boundary relative to the continuity of reflections. Where any two seismic profiles intersect, the TWTT position of the interpreted stratigraphic units was matched between the lines. At multiple times, I also examined broadly an emerging correlation of seismic reflections to geological units in comparison to the reference area reflection patterns, near Kesselring, and either confirmed the consistency of interpretation, or altered the interpretation to achieve consistency.

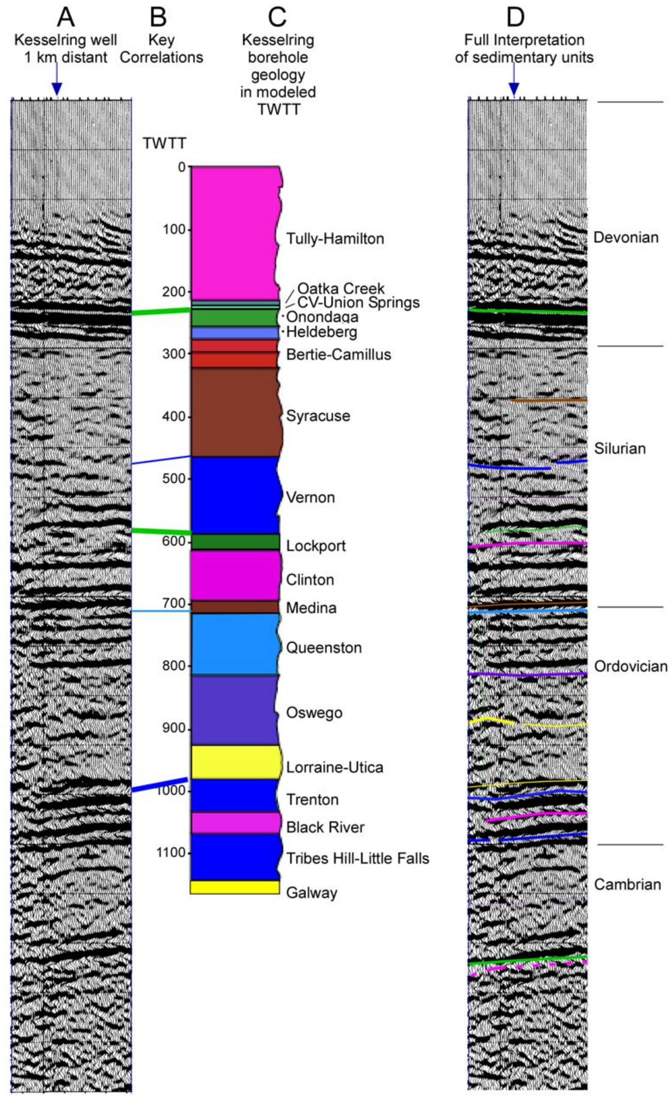


Figure 3. Comparison of Kesselring borehole geological column, modelled in two-way travel time, to a nearby column of seismic reflection data. Thick lines indicate correspondences between formation boundaries and seismic reflectors that are considered to be most physically reliable; thin lines mark boundaries that may also be directly comparable to reflections. Geologic time labels on right are referenced in the text to refer to the indicated intervals of reflectors. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

4.2. Deformation features

Disruptions to simple linear continuity and parallel disposition of neighboring reflections are interpreted as geological structures in cases where processing artifacts and depositional geometries can be ruled out. As shown in Figure 4, these are identified based on either shifts in the vertical positions of continuous reflections in a wavelike pattern (folds), or interruptions of the lateral continuity of reflections (faults). Three classes of structures are color-coded in the interpretations (Fig. 4): axes at which continuous reflections reverse their directions of inclination are either convex (dark green, anticlines) or concave upwards (light green, synclines); breaks in continuity of the reflections (faults) are indicated in purple. Subdivisions of these groups are treated separately in the results.

Smith (2006) published seismic images to display the interpretation of faults associated with natural gas reservoirs identified in two gas fields of the “Trenton – Black River grabens” type (referred to here as TBR). The illustrated characteristics of disruption in the Trenton and Black River formations guided recognition of similar features in the Ithaca-area seismic data; Smith’s interpretation of the downward continuity of the structures, within the “basement,” are considered as one among a family of possible interpretations.

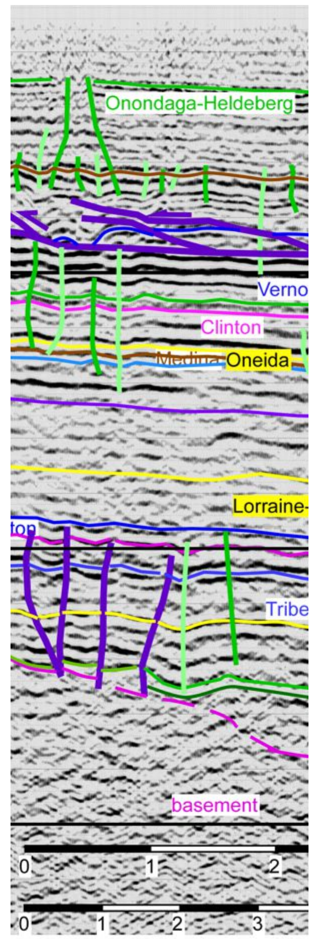


Figure 4. A segment of a reflection profile, showing interpreted sedimentary units (compare to Figure 1) and four classes of structures: anticline axes (dark green), syncline axes (light green), thrust faults (subhorizontal purple lines with arrows marking apparent slip directions), near near-vertical faults (sub-vertical purple lines). Horizontal scales are in miles (upper) and kilometers (lower). Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell

4.3. Identification of contact of sedimentary rocks with crystalline basement

The contact between overlying sedimentary rocks and underlying crystalline basement rocks ought to be recognizable in reflection seismic data because of the contrast between the pattern of laterally extensive reflections in the sedimentary rocks, and the lack of this pattern in crystalline basement. However, several factors decrease the quality of seismic reflection data with increasing subsurface depth, which interfere with recognition of the upper contact of basement. A factor that varies from line to line, is the degree of data degradation caused by environmental noise: two of the seismic lines were collected along busy roads and display poorer resolution of reflections at all depths, whereas the other lines include only segments with high levels of traffic noise. A depth-dependent factor is that the strength of seismic reflection data decreases with increasing depth due to attenuation of the sonic energy. A second depth-dependent factor is that reverberations of the sonic energy can create the appearance of subhorizontal reflections at long travel times. These “multiples” appear at travel times corresponding to the crystalline basement, and they can be confused with legitimate sedimentary rock reflections. The multiples can readily lead to an erroneous interpretation of the position of the top of basement.

In the available industry seismic profile data set, two of the profiles display over most of their lengths a clear distinction between an overlying zone with subhorizontal reflections, and an underlying zone with discontinuous reflections at various orientations (Fig. 5). These two areas are taken as reference locations for the likely position of the top-of-basement. From them, the interpretation of generally similar patterns is extended across other profiles. It is common that other profiles display poor data quality at comparable depths (Fig. 6). Consequently, the true position of the basement contact and the geometry of the contact, are two products with relatively low degrees of certainty across a significant fraction of the data set.

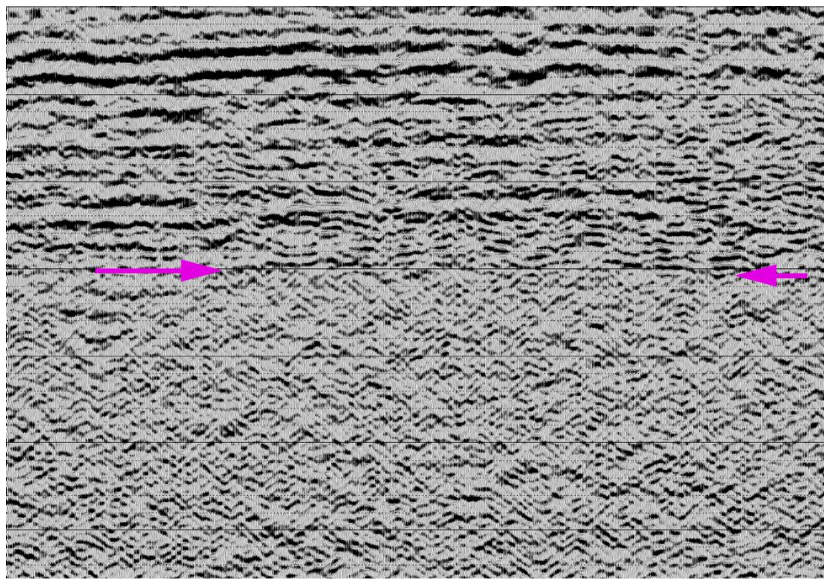


Figure 5. The pattern of laterally continuous reflections changes downward to a pattern of discontinuous reflection segments, many of which are steeply inclined. The pink arrows mark the position interpreted to be the contact between layered sedimentary rocks (above) and crystalline basement (below) in this seismic profile with good data quality at these depths. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

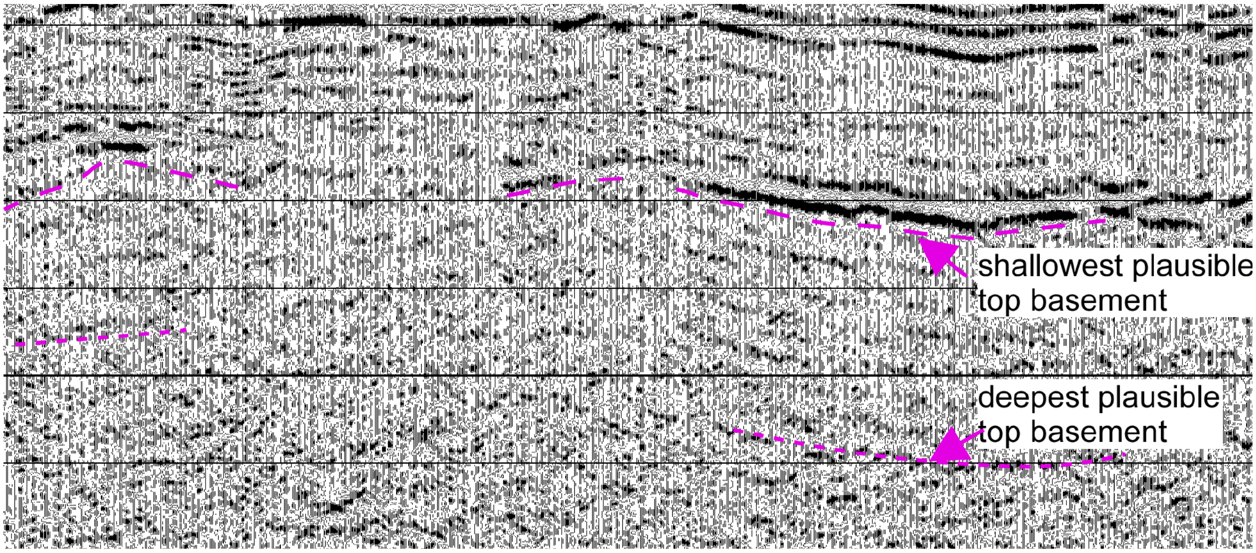


Figure 6. This seismic profile displays two zones (left quarter and right half) in which multiples of reflections overprint the low reflectivity of basement. This generates a wide zone of uncertainty in the correct interpretation of the top of crystalline basement. In an intervening zone (left of center) there is poor data quality through the lower zone of sedimentary rocks and in the basement, which leads to a lack of criteria on which to base the interpretation of the top of basement. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

5. General features discovered through analysis of regional data set

5.1. Spatial distribution of sedimentary units

The seismic data (Fig. 7) indicate that all the sedimentary rock lithological groups (Figs. 2, 3) above the basal Potsdam Formation persist throughout the area of study (Fig. 1B). Whereas the lateral variability in reflection properties may contain valuable information about variation in the compositions or thicknesses of interlayered rocks, these features have not been analyzed.

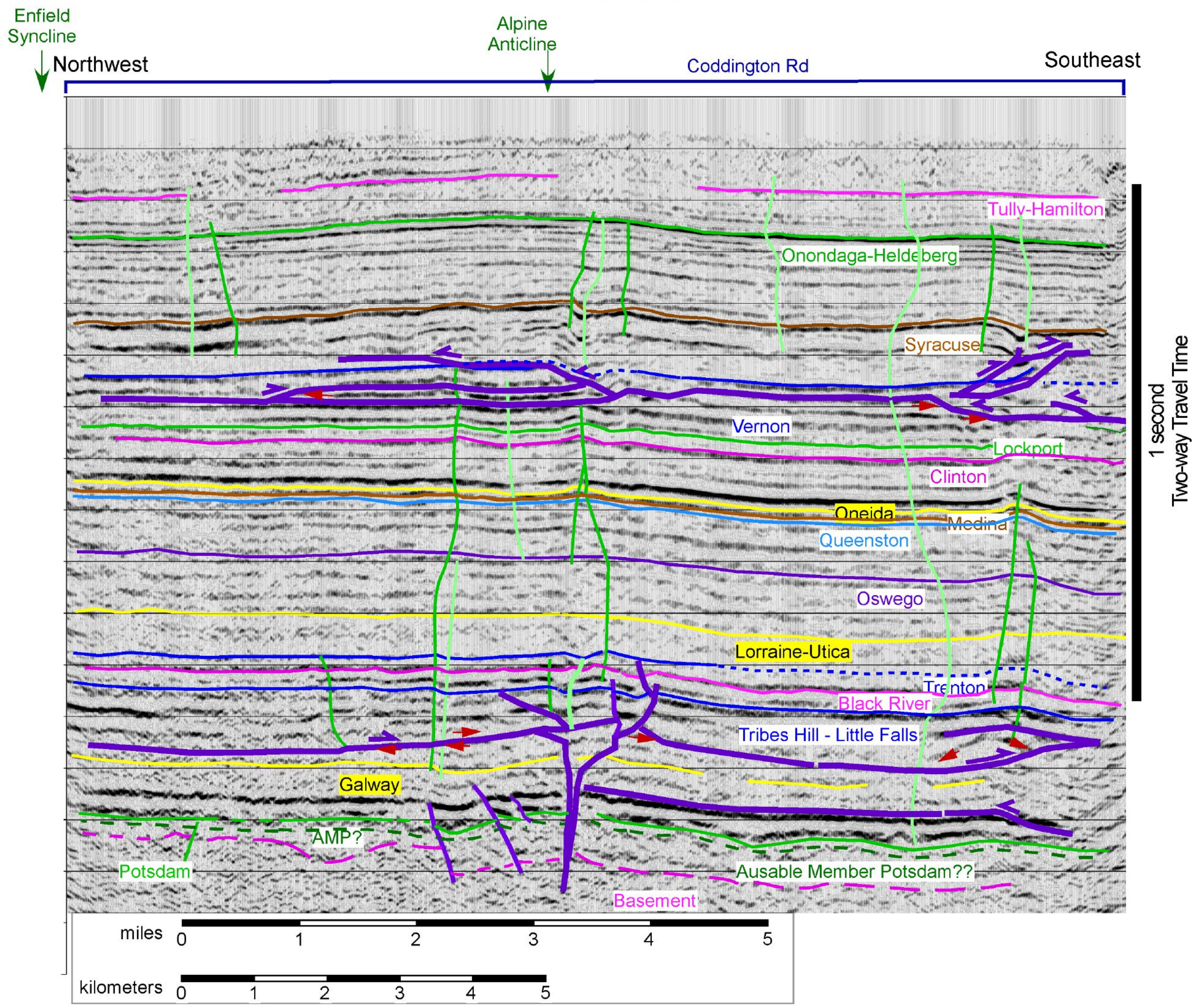


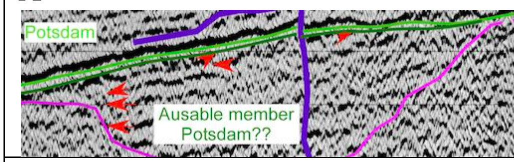
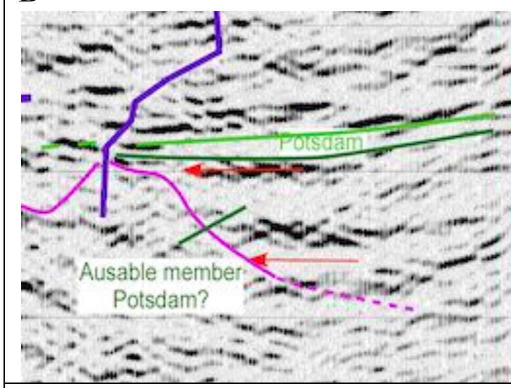
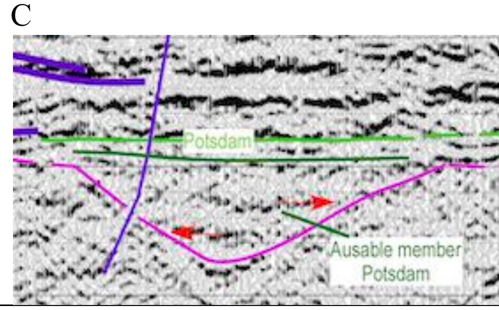
Figure 7. The seismic reflection packages corresponding to the lithological units illustrated in Figures 2 and 3 persist laterally throughout the grid of seismic profiles, with the exception of the basal unit (between the lowest pink line and the overlying green line), the Potsdam Formation. Whereas in detail the continuity of individual reflections is interrupted by small magnitude folds (near-vertical green lines) and faults (purple lines), the sedimentary rock identifications can be tracked across those structural features. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

5.2. Paleo-valleys at the upper surface of crystalline basement

The lowest sedimentary rock unit known in New York state, Ontario, and Quebec is the Cambrian Potsdam Formation. The formation is exposed at the surface around the margins of the Adirondack Mountains; it is an important aquifer in Quebec and the extreme northern sector of New York (Williams et al., 2010). An upper sandstone dominated by quartz sand is reported to occur widely, and to have been deposited by marine transport of sedimentary particles (Selleck, 2008). One or two lower members with conglomerate and sandstone of more varied rock fragment and mineral composition occur in the Champlain Valley and on the northern margin of the Adirondacks, and reportedly formed by short-distant transport of sedimentary materials in river systems across the eroding upper surface of the crystalline basement (Selleck, 2008). Al Aswad (2019) examined sparse borehole logs that are able to detect the presence of potassium, an element in the mineral feldspar, and sparse cuttings from several boreholes in the southern Finger Lakes region (Fig. 1, boreholes near Avoca, Shepard, Olin). She interprets that the lower member of the Potsdam (Ausable member) occurs in some, but not all, of the subsurface near and within Tompkins County, and that the quartz-dominated upper member is only 50-100 ft (15 – 30 m) thick. Al Aswad (2019) also notes that porosity and permeability are reportedly enhanced in the Ausable member, making this a potential reservoir target for geothermal energy extraction.

The reflection pattern identified as the contact of Galway Formation over Potsdam is readily traceable through much of the seismic data, though not in parts of some lines where there was low data quality. Below an upper interval, about 100–200 ft (30–60 m) thick, in some sectors of the high quality profiles, the underlying materials display the short, irregular reflections typical of crystalline basement. But in other parts of the same profiles, there are well ordered, sub-horizontal, moderate strength reflections below the regionally extensive upper Potsdam (Table 1). Some of these may be ancient valleys eroded into the top of the crystalline basement, which filled with sedimentary debris, prior to the deposition of the regional sheet of sandstone. Nevertheless, the inconsistent quality of reflections near the interface between sedimentary rock and basement lead to the likelihood that some of the features that are mapped as possible paleo-valleys, may instead be multiples in the seismic data. Consequently, maps showing the distribution of the possible paleo-valleys identify two classes: those based on apparently reliable data, and those based on more ambiguous data.

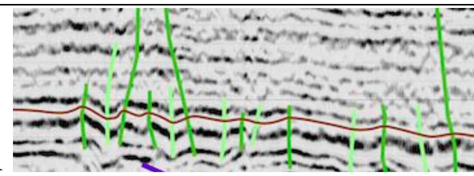
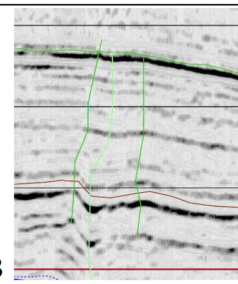
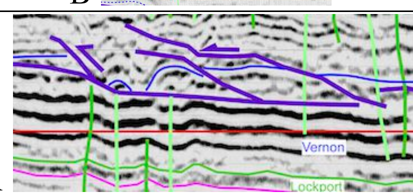
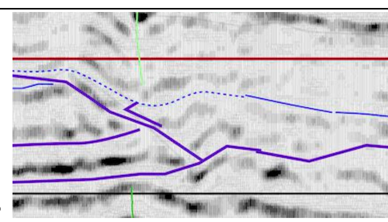
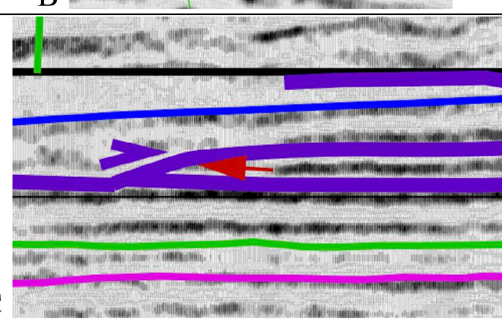
Table 1: Description and examples of the seismic reflection evidence for paleo-valleys overlying the top of crystalline basement, filled with strata attributed to the lower (Ausable) member of the Potsdam Formation. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

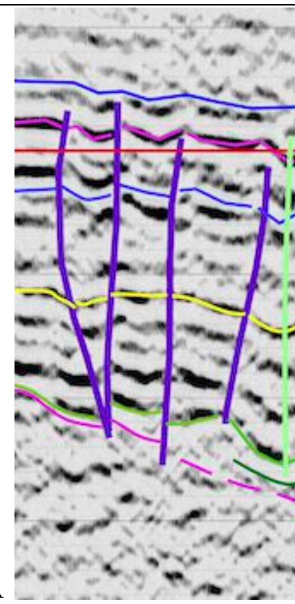
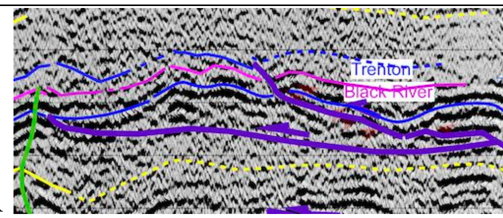
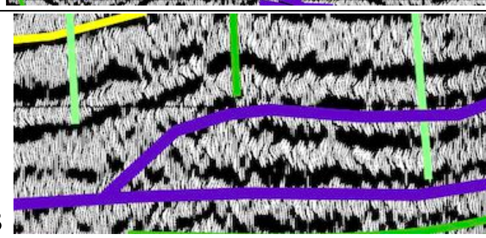
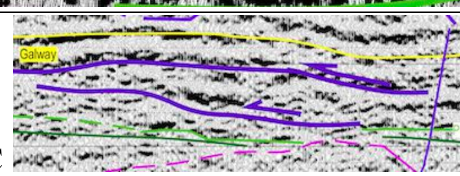
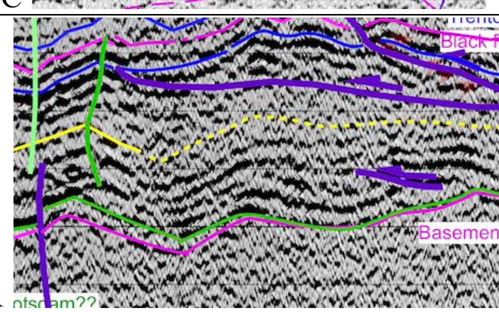
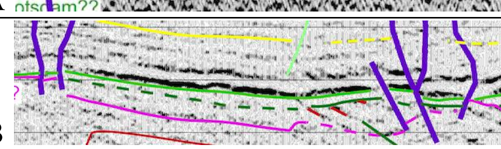
Structural feature category	Description	Illustration
Paleo-valleys at top of crystalline basement in which Cambrian strata (Potsdam Formation) are anomalously thick	The reflector interpreted to be the top of Potsdam is strong and laterally persistent through much of the data set. A, B, C) In locations with a strong contrast between layered sedimentary rocks and disorganized basement reflections, in local areas the contact with basement appears to deflect downward. Above these U-shaped deflections there is a fill of long wavelength, moderate strength reflections. A second green line is drawn to separate the regional Potsdam from the localized sedimentary rocks that appear to fill paleo-valleys.	A  B  C 

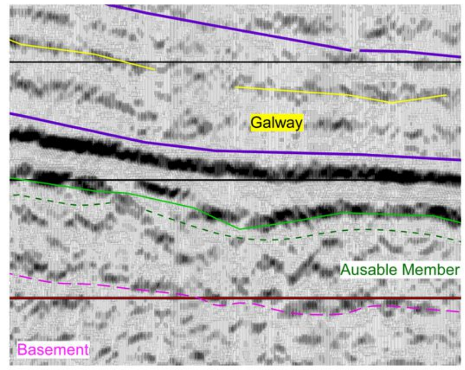
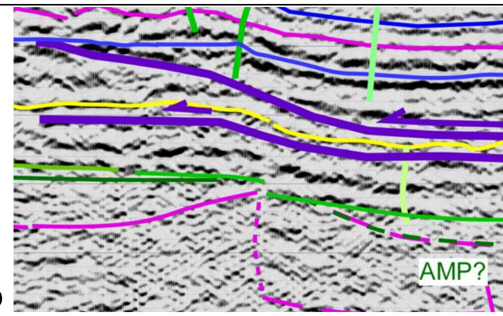
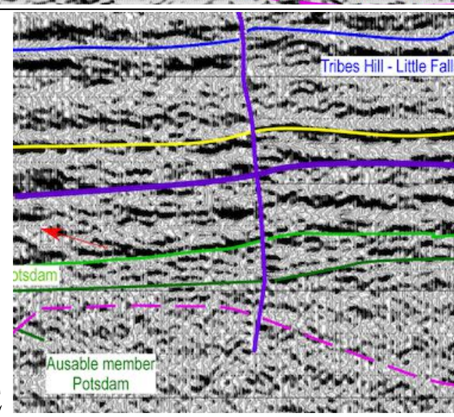
5.3. Structural feature categories identified in the complete seismic profile dataset

The broad suite of categories of structural deformation features identified in the full region of study (Fig. 1B) sets the limits for the structures mapped in the data for the immediate surroundings of Cornell. The major structures of the full regional data are shown on the interpreted seismic lines, placed in Supplemental File 2. The categories of structures are described and illustrated in Table 2.

Table 2: Categories of structural deformation features identified in the region-wide seismic industry reflection profiles (Fig. 1B). Rock unit names correspond to Figures 2 and 3. Near-vertical, green lines mark fold axes. Purple lines mark faults. Other colors of lines, and sub-horizontal green lines, are contacts between sedimentary rock units (fully labeled in Fig. 7). All examples display horizontally-squeezed data, which vertically exaggerates the inclinations of the reflections, to make them more readily visible. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

Structural feature category	Description	Illustration
1. Folds that approach surface	Upright folds. Two major folds (wavelengths X km, relief Y m) correspond to Wedel's (1932) Alpine anticline (wavelength 7 km, relief ~ 120 m) and Firtree Point anticline (~11 km wavelength, relief about 20 m); no similar-scale folds occur between these. More abundant folds (A, B) have average wavelengths <1 km, and relief <20 m.	A  B 
2. Folds and thrusts within the Syracuse and Vernon Formations of the Salina Group	A, B) Folded reflections terminate against faults. These faults are parallel to major reflections with differing folds. C) A reflection terminates between two adjacent continuous reflections (red arrow marks termination). This is interpreted to be evidence that a bedding-parallel fault ramps across sedimentary layers to higher slip zones.	A  B  C 

3. Steep faults that disrupt deep strata (Galway, Tribes Hill – Little Falls, Black River, and Trenton units) and can be tracked downward to basement contact (TBR)	The reflections in the Ordovician interval display short wavelength (~0.5-1 km) folds in a vertical succession of reflections, with discontinuities between adjacent minor folds. Tracing downward the positions of discontinuities commonly determines that they approach and, in some cases, merge with neighboring discontinuities. These are like forms of TBR structures shown by Smith (2006).	A 
4. Thrust faults and fault-bend anticlines/synclines in the Cambrian-lower Ordovician section (especially Galway and Tribes Hill - Little Falls units)	A, C) Folded reflections terminate against faults that are parallel to major reflections with differing folds. B) A reflection terminates between two adjacent continuous reflections. This is evidence that a bedding-parallel fault ramps across sedimentary layers to a higher slip zone. Overlying reflections display a fold that does not continue downward below the thrust fault.	A  B  C 
5. Broad anticlines and synclines in the Cambrian strata that conform to the basement-sedimentary contact.	In some areas (A-C), two prominent, laterally persistent reflections in the middle to lower Galway unit, and adjacent reflections in the Potsdam, reveal folds with wavelengths of 1-4 km. With a significant uncertainty, it is interpreted that the contact of layered sedimentary rock over basement possesses a coherent fold form. D, E) For a subset	A  B 

	of cases, the folded form of the Galway reflectors corresponds to the interpreted margin of a Potsdam paleovalley. Faults in the basement that may be integrally related to these folds are not identified in the migrated reflection profiles. Example A is for 1984 data collected in steep-walled valley. Examples B, C and D are from 2007 data collected adjacent to valley walls. Example E is for 2007 data collected across quite level topography. A basement fault of the TBR family is interpreted (sub-vertical purple line), but its offset seems insufficient to explain the fold relief. Based on the data and terrain, the reliability that there exists a fold in A is assigned high uncertainty; a fold in B-D is assigned intermediate uncertainty; a fold in E is assigned low uncertainty.	 C  D  E

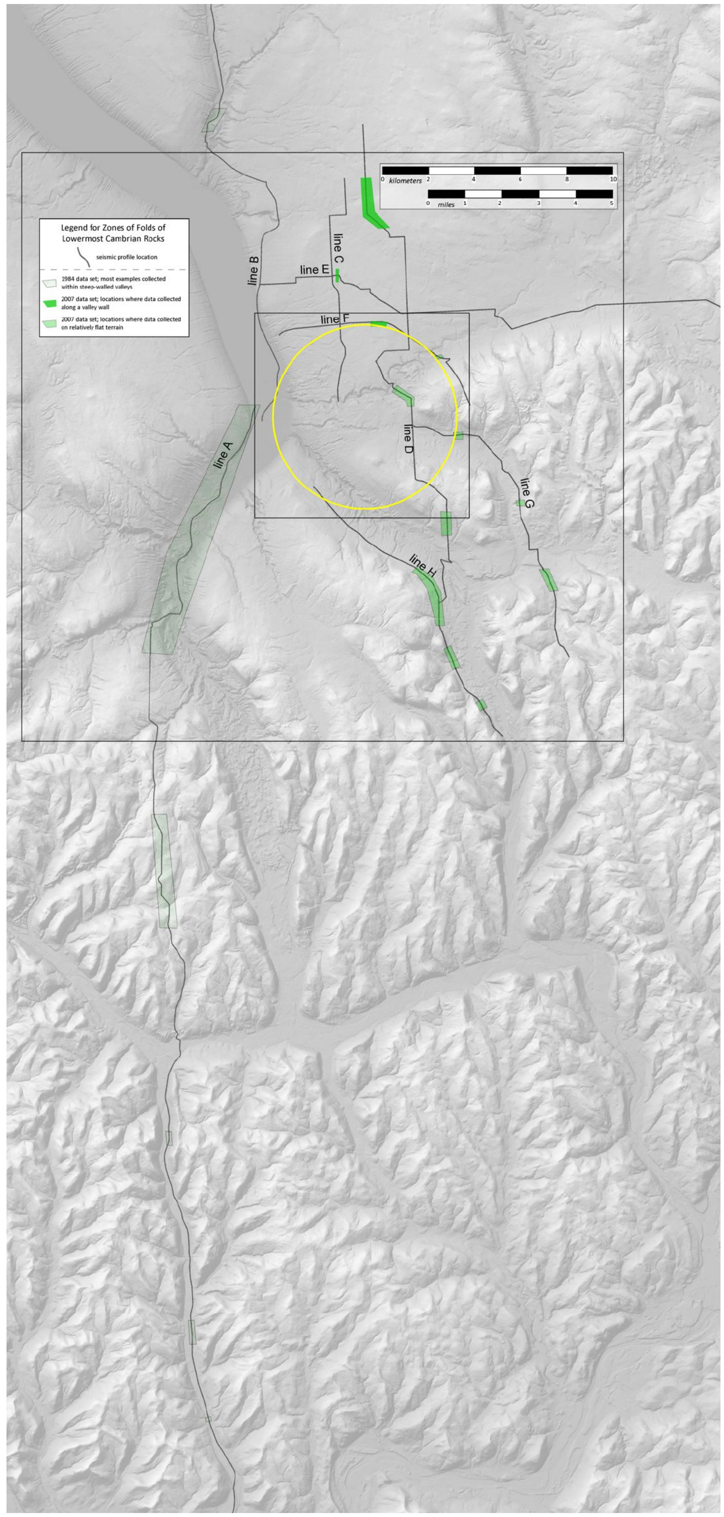
5.4. Uncertain nature of broad anticlines and synclines in the lowest Cambrian strata

The kilometer-scale anticlines and synclines in the Cambrian strata that conform to the basement-sedimentary contact (Table 2, category 5) pose a special challenge for structural interpretation. The challenge is large due to the low quality of reflection data for the basement contact zone, and due to the existence of multiple alternative explanations for relationships of such folds to faults.

The 1980's vintage seismic data display a series of marked apparent folds in a profile that runs from near the Pennsylvania border to the south end of Cayuga Lake (Fig. 1B; Table 2, category 5, example A). However, the series of apparent folds coincides with an interval in which the data were collected within the Cayuga Inlet valley (Fig. 8), for which the geometry of reflecting sound waves may have been complicated by the bedrock walls of the valley. Where that same profile and another collected in the same campaign are not within a deep valley, there exists a single example with the appearance of a folded basement contact. For those data, the folded form of the reflections may not be physically real parts of the rocks. Star Geophysics reprocessed a sector of the 1984 data which contains the series of apparent folds. Their seismic image lacks the series of folds, perhaps confirming that they are not physically real features. However, the reprocessed images also lack any coherent reflections below 600 msec, which indicates that both noise and useful information have been lost. The examples whose data source is the 1980s surveys are distinguished in the summary maps.

The other pictured examples (Table 2, category 5, B-E) are from the 2007 seismic data, and all of the 2007 examples are basement-surface folds are comparatively subtle. Over half of the examples occur where the seismic data were collected across a strong topographic gradient at a valley margin (Table 2, category 5, examples B-D; Fig. 8, light green polygons), again raising a concern that the geometry of reflecting sound waves might by influenced by the irregular upper surface of sedimentary rocks in the Ithaca region. However, the 2007 data traverse numerous other valley margins without corresponding to apparent basement-contact folds, preventing a simplistic interpretation that the observed fold-forms are artifacts of the seismic data. L. D. Brown and D. May (personal communication, 2019) examined the possibility that a non-straight line along which the seismic profile nearest Cornell was collected could explain an apparent deep fold form. They concluded that the line geometry is not responsible for the fold form. In the summary maps, sectors for which 2007 data is the basis for interpretation of these deep folds are distinguished as moderately uncertain (collected near valley walls) or less uncertain (collected across topographically simple regions).

Figure 8. Regions in which apparent fold forms in the lowermost sedimentary rocks may be indicative of a near-vertical fault in the basement. Three classes of data quality are distinguished, related to the vintage of the seismic data and its processing, and the location of the seismic data relative to steep topographic slopes that may have caused complex sonic wave reflection paths that are not fully corrected in the processing of the reflection profiles. Note that the older data set exists west of Ithaca, that the 2007 data that cross topographic slopes exists south and east of Ithaca, and that the 2007 data collected across largely flat terrain occurs north of Ithaca. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.



If these folds are physically true, then the structural explanation for them is a second challenge. A routine premise of structural geology is that typical crystalline basement rock is not mechanically capable of folding at wavelengths similar to layered sedimentary rock, and therefore that brittle faults likely exist in basement rock if the immediately overlying sedimentary layers are folded. However, in light of a) the widespread occurrence of thrust faults in the Cambrian Galway through Ordovician Tribes Hill units, and b) the widespread poor seismic resolution of the contact between basement and sedimentary rocks, it is likely that sub-horizontal thrust faults at or very near the basement contact could produce the fold geometries noted. With available information, either steeply-dipping faults that penetrate the basement or thrust faults within a short vertical distance of the sediment-basement discontinuity, are equally likely explanations. Figure 9 illustrates these two classes of alternative fault-related explanations, and variants within each explanation.

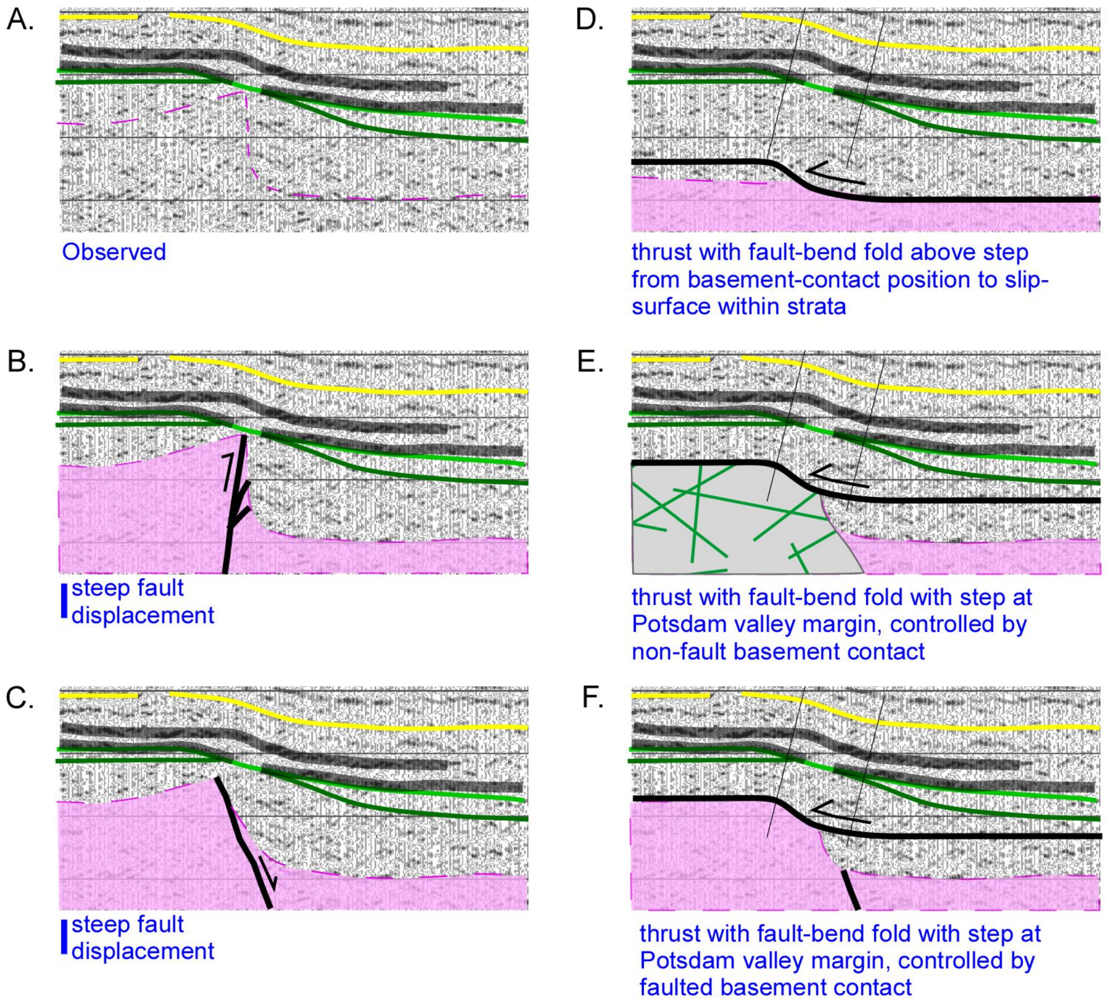


Figure 9. Alternative interpretations of the observed (A) fold geometry within the Galway that appears to continue downward to the Potsdam-basement contact. B and C illustrate scenarios in which a sub-vertical brittle fault creates a step in the basement surface that matches the vertical offset across the fold. D-F illustrate scenarios in which a thrust fault within the Potsdam Formation or at the Potsdam – basement contact produces a fold over a fault ramp. Given available data, either a near-vertical fault or a thrust fault is equally likely.

Some of the zones with apparent folds in the deepest sedimentary layers include TBR graben structures. For these cases, it is relatively straightforward to expect that a TBR fault zone could serve a second function, as a fault zone in scenarios B or C of Figure 9. These are cases in which a suitable fault is directly indicated by the seismic reflection data. Nevertheless, there exist several cases (e.g., Table 2, category 5, example B) for which there is no direct evidence for an appropriately located sub-vertical fault, and such a fault is purely hypothetical.

6. Features identified in Tompkins County, with emphasis on the subsurface within 4 km (2.5 mile) distance of Cornell east-central campus

6.1. Tompkins County generally

Figure 10 illustrates the locations in the central sector of Tompkins County at which the subsurface contains all the categories of features described in Tables 1 and 2. The distribution of the individual classes of features is shown in Figures 12-15, and 17. Features located within the 8 km (5 mile) diameter yellow circle, centered on the eastern margin of the highly developed campus region, are described individually.

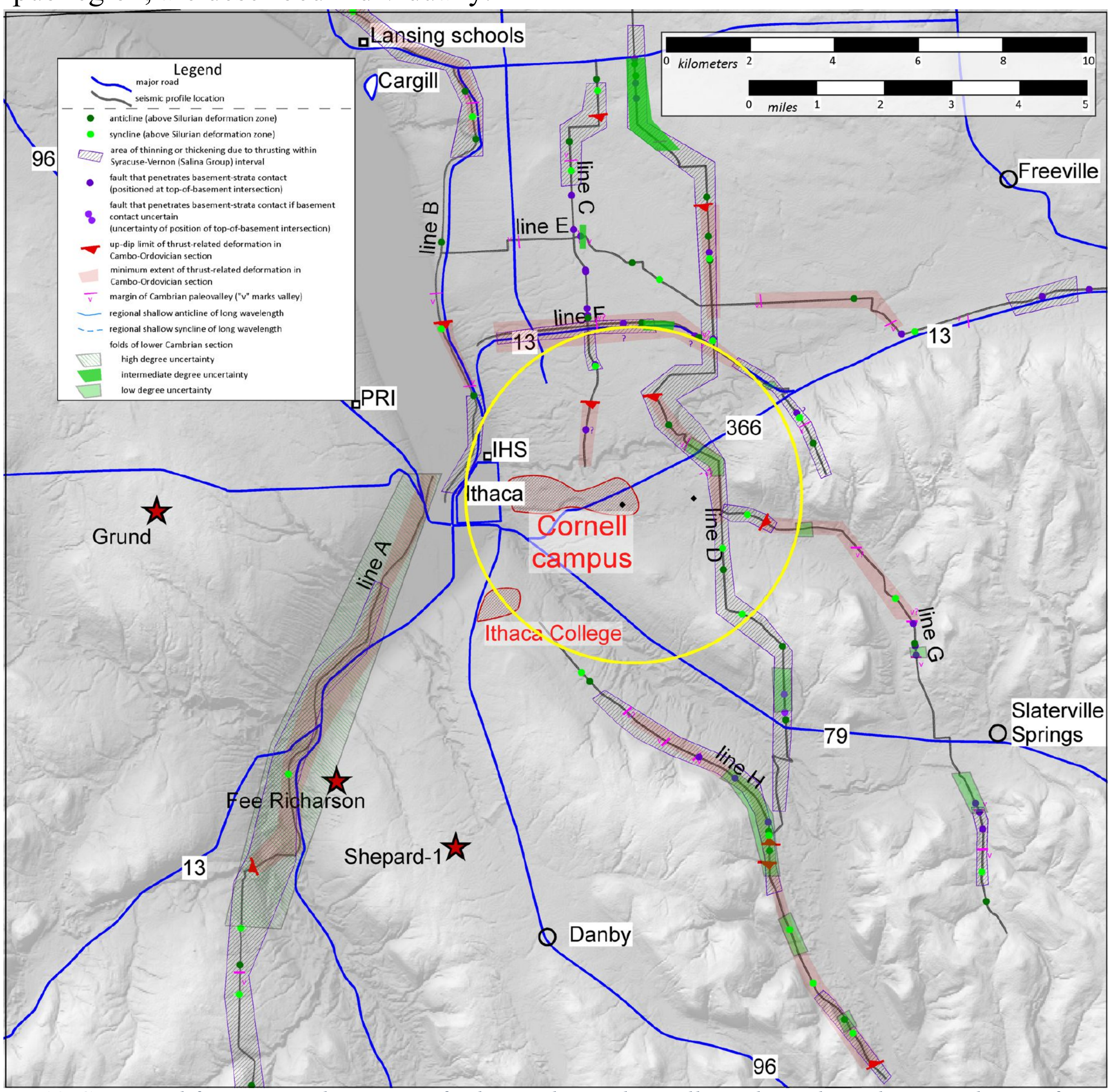


Figure 10. Structural features, and margins of sub-Potsdam paleo-valleys, throughout the central part of Tompkins County (field of view 26 km [16 miles] wide). Circle marks a 5-mile-wide area centered near east margin of Cornell's campus. Black diamonds mark two sites under consideration for a test borehole. Gray lines are locations of leased industry seismic profiles (Seismic Exchange Incorporated). Red stars mark deep boreholes used as controls on subsurface geology.

Folds that reach near the surface are of two classes, long-wavelength regionally continuous folds (wavelength ~7 km), and short-wavelength folds (wavelength <1 km) that may be of short lateral continuity. The distinction is illustrated in Figure 11. The positions of long-wavelength folds are used to refine Wedel's (1932) map of surface folds in the subsequent maps.

Examples of the uncertain fold-forms near the top-of-basement are illustrated in Figure 16, and their distribution shown in Figure 17.

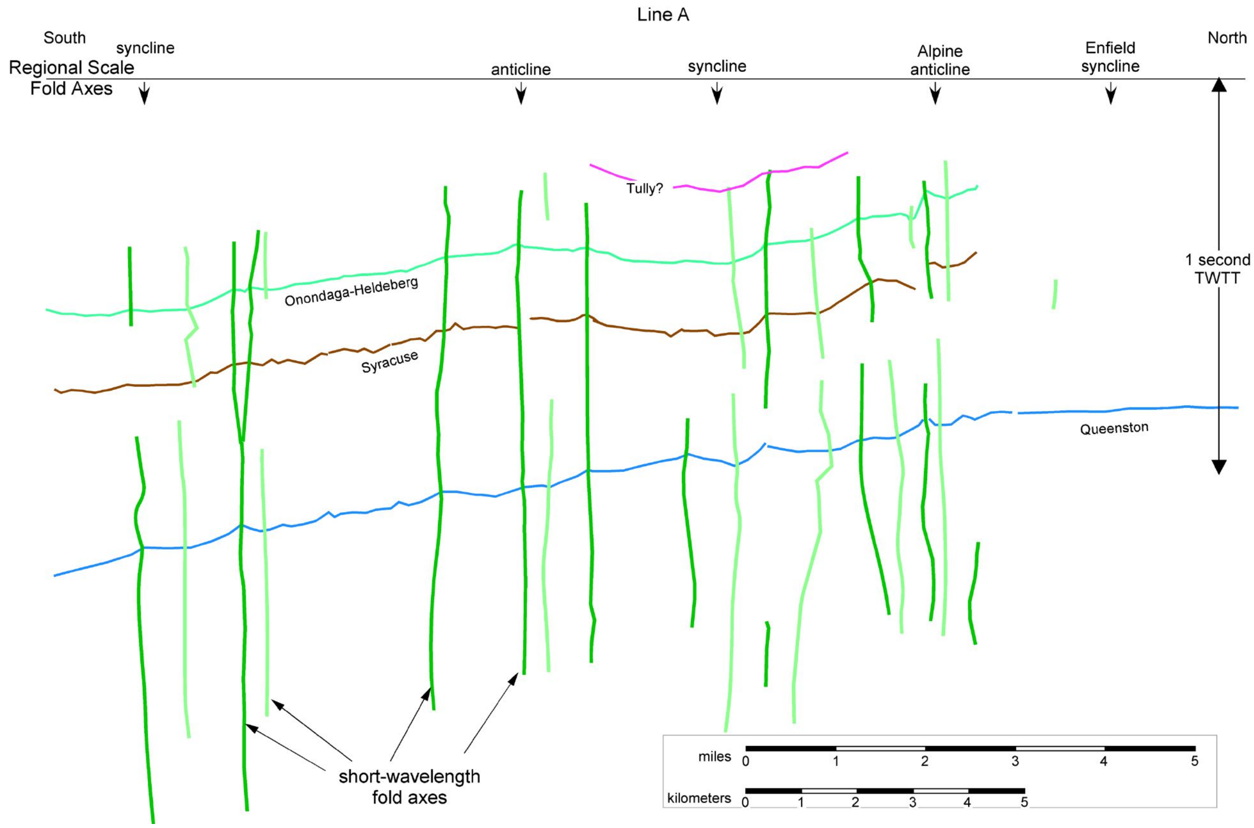


Figure 11. In a long north-oriented seismic profile, long wavelength folds (whose hinge zones are marked along top of section as synclinal or anticlinal forms) are visible in the several-kilometer wide alternating lows and highs in the contacts of four sedimentary unit. The axes of short-wavelength folds are traced with near-vertical dark green (anticline) and light green (syncline) lines.

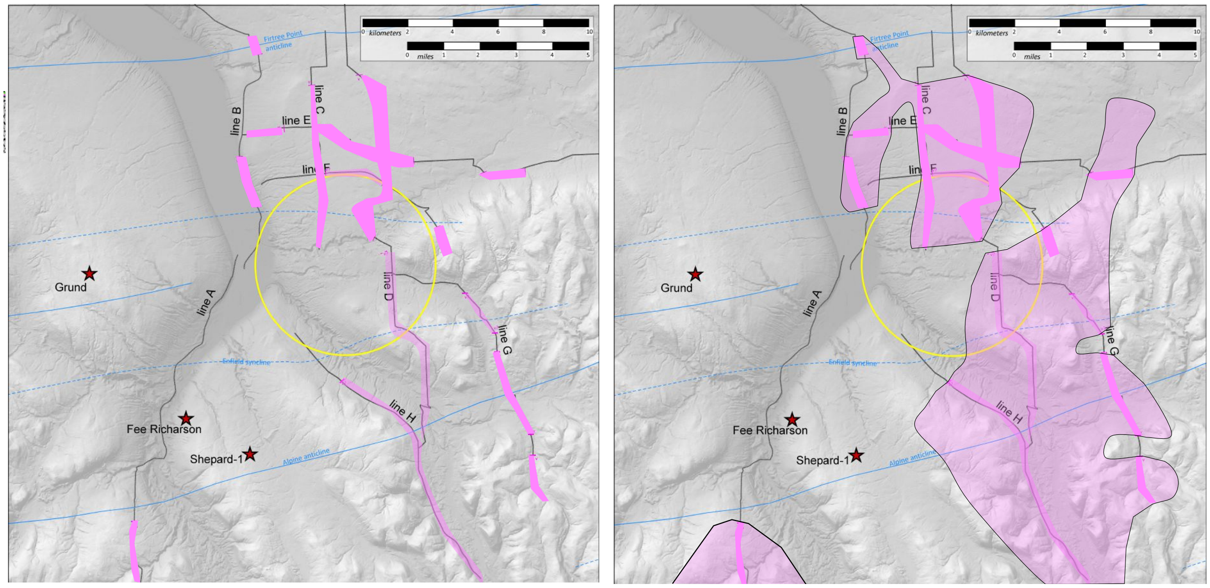


Figure 12. Distribution of interpreted paleo-valleys at the contact between underlying crystalline basement and the Potsdam Formation. A) Observed spatial limits of paleo-valleys (medium pink is more certain than pale pink). B) An interpretation of the extent of paleo-valleys, represented by pink polygons, extrapolated from the seismic profiles and Shepard-1 borehole, to the region more broadly. Numerous alternative interpretations are equally plausible, as long as they respect the data in (A). Pale blue lines are folds known from surface data. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

Figure 13. Locations identified as subsurface small-scale fold axes that approach the surface. Broad zones of thrust-related deformation within the Syracuse Formation and Vernon Formation are enclosed in polygons with purple cross-hatch. Blue lines mark larger scale anticlines and synclines known from surface mapping and seismic interpretations. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

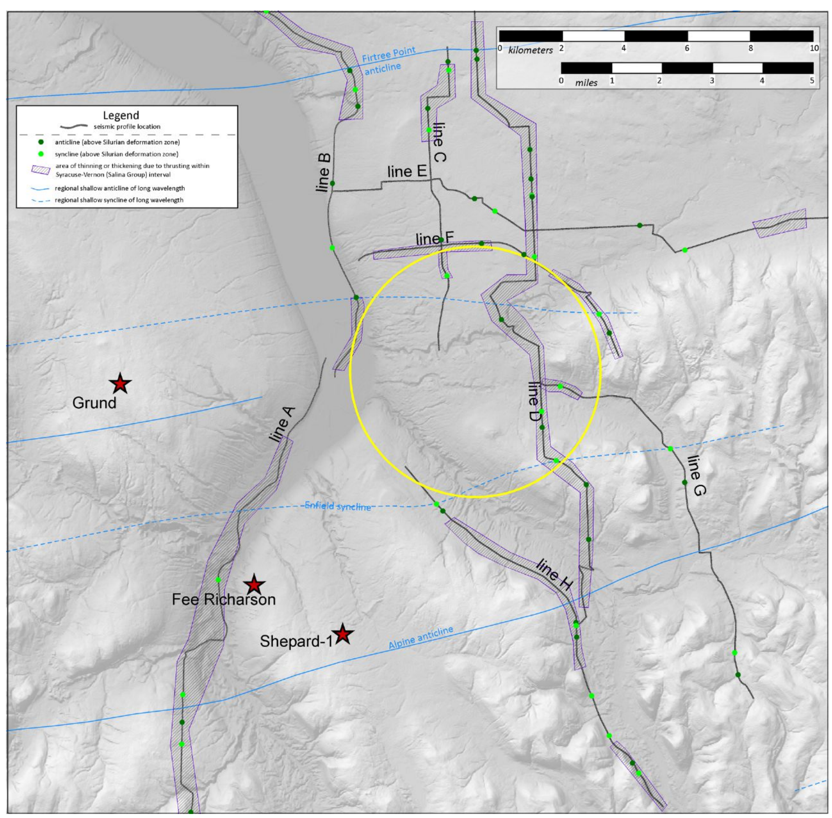
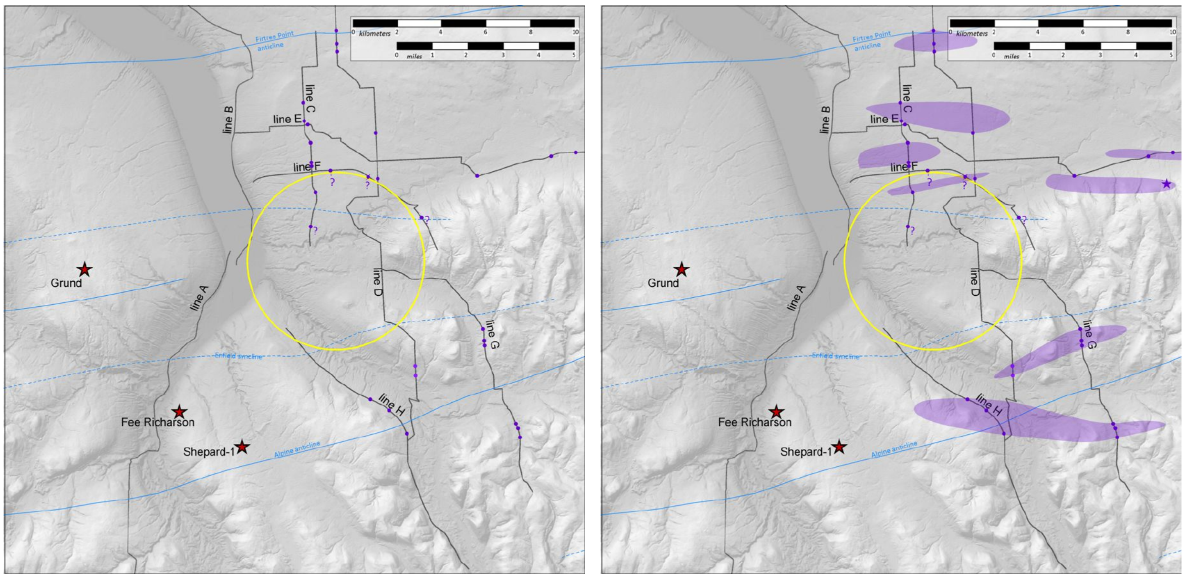
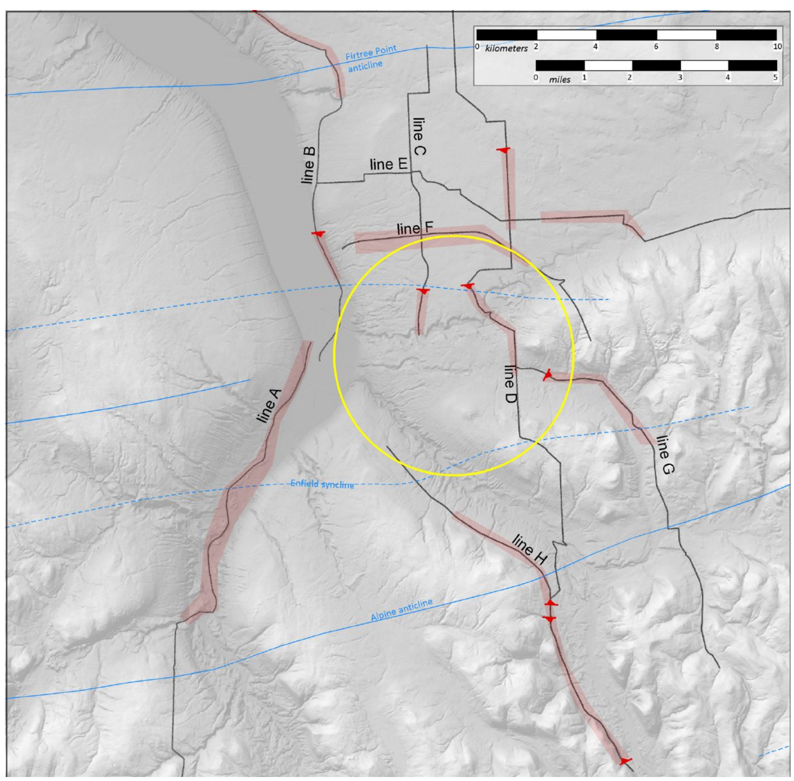


Figure 14. A) Distribution of sub-vertical faults that affect Cambrian and Ordovician strata, with style of Trenton-Black River (TBR) grabens. Locations correspond to position where the imaged fault appears to intersect the top of basement. Question marks indicate uncertainty about the classification of the observed features as sub-vertical faults that intersect the top of basement. B) Clusters of TBR faults that align ENE or near east-west. These zones are similar in dimensions and orientations to the TBR grabens of counties southwest and west of Ithaca (Fig. 1A orange polygons). Not all faults classified as TBR occur within clusters. Blue lines mark large-scale anticlines and synclines known from surface mapping and seismic profile interpretations. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.



A B

Figure 15. Distribution in the subsurface of zones of bedding-parallel thrust faulting (polygons with pale red fill) within the Cambrian (Galway) and Ordovician (primarily Tribes Hill-Little Falls) interval. Heavy red lines with triangles mark the up-dip limits of steps of thrust sheets across sedimentary units (expressed as reflections) (Table 2, category 4, illustration B). Blue lines mark anticlines and synclines known from surface mapping. Gray lines show locations of seismic profiles. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.



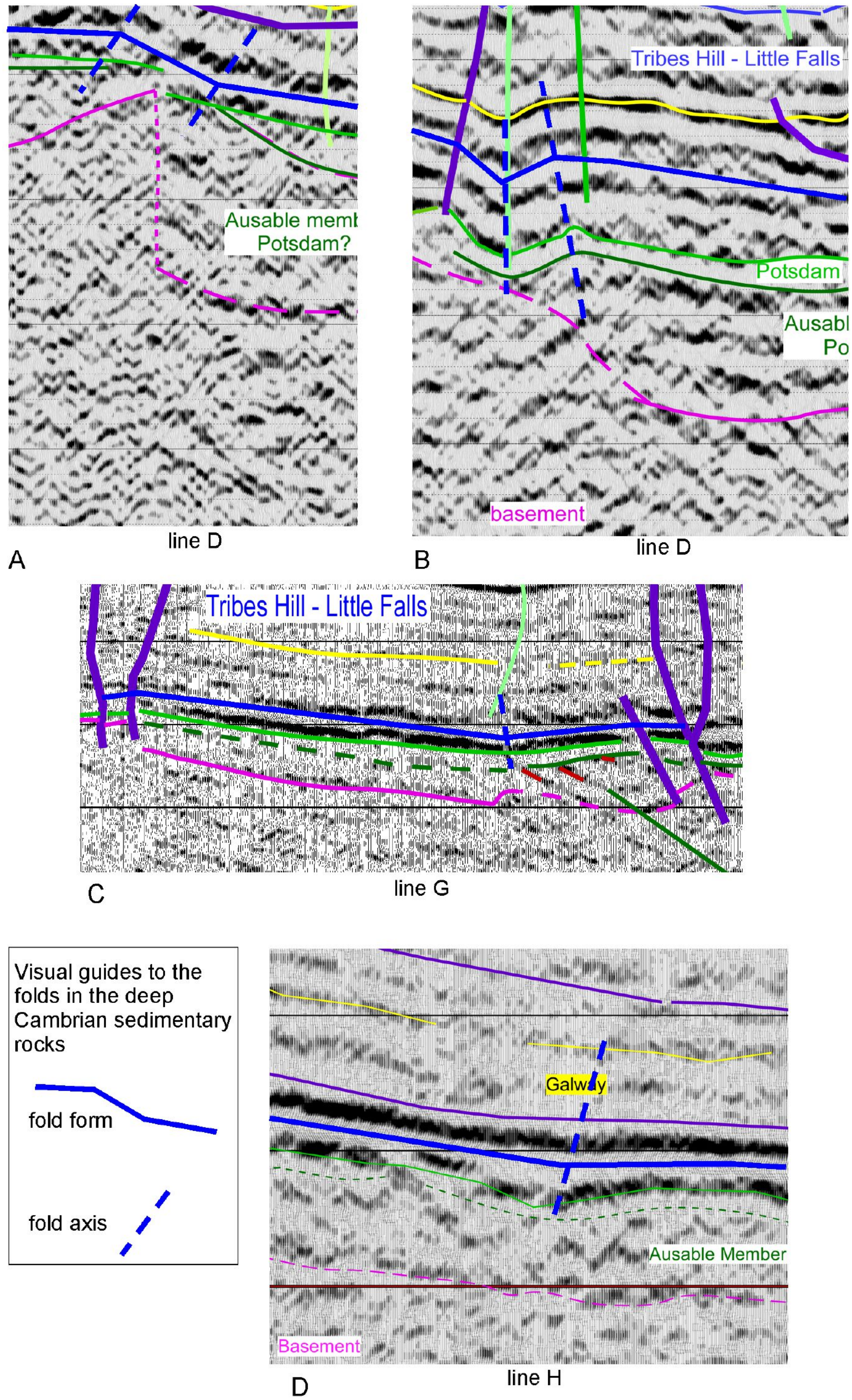


Figure 16. Examples of fold forms near the base of the sedimentary rocks in the near-Ithaca region of focus, for which the interpretation is highly uncertain. All data are from the 2007 surveys, and thus of overall high quality. Color code for sedimentary unit identifications (sub-parallel) and structures (sub-vertical) are as in Figure 3 and Table 2. Blue lines (see legend) are added as visual guides to the fold-forms of category 5. Examples A, C, and D all correspond to a part of a seismic profile that crosses a topographic step between lowland and steep hillside. Example B is an example of a fold-form where the seismic profile was collected across comparatively flat-lying terrain. Example B reveals a close association of the fold with a TBR-style fault (sub-vertical purple line). The extreme ends of the example C fold form also correspond with TBR-style faults that project down into basement. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

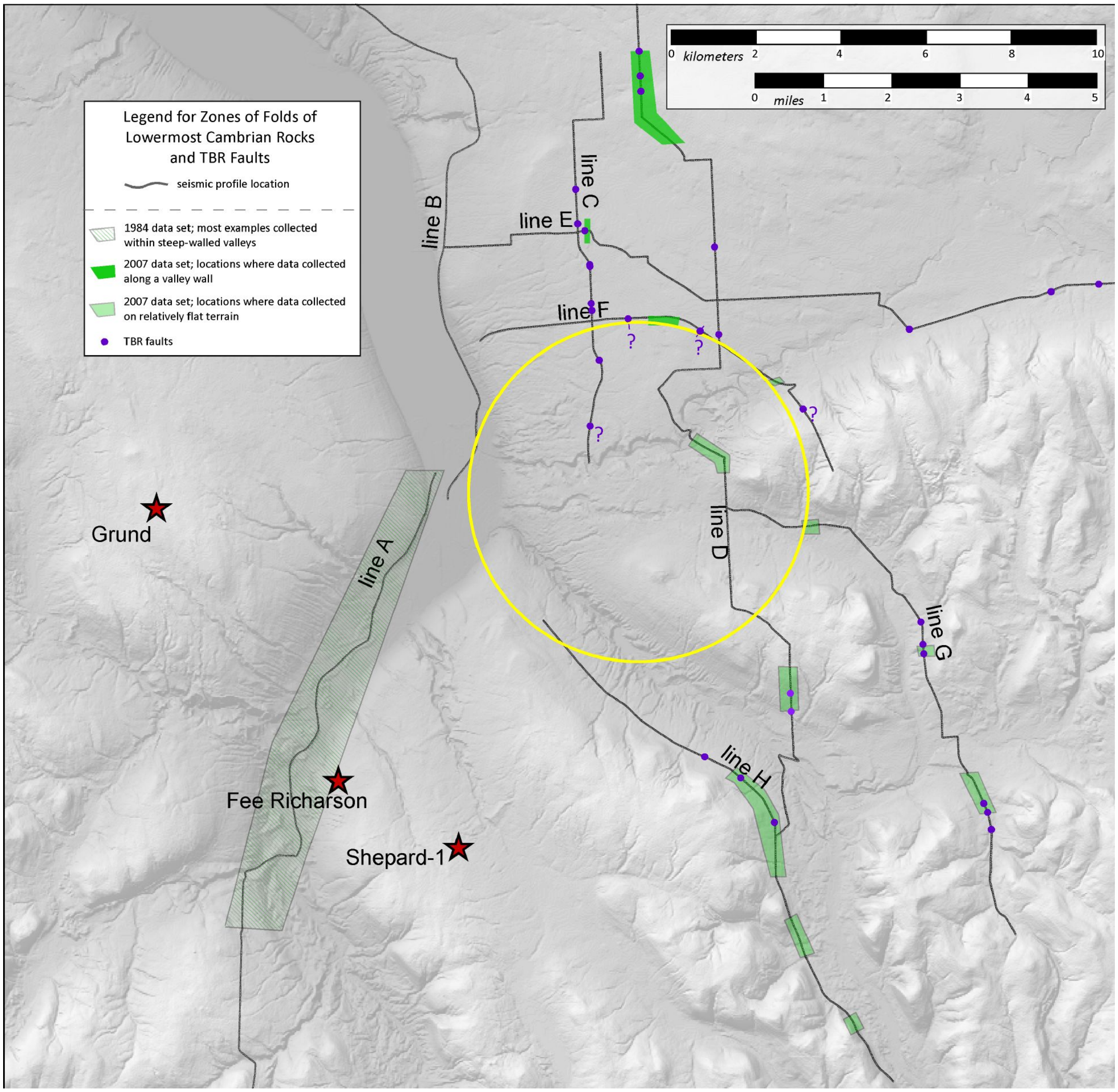
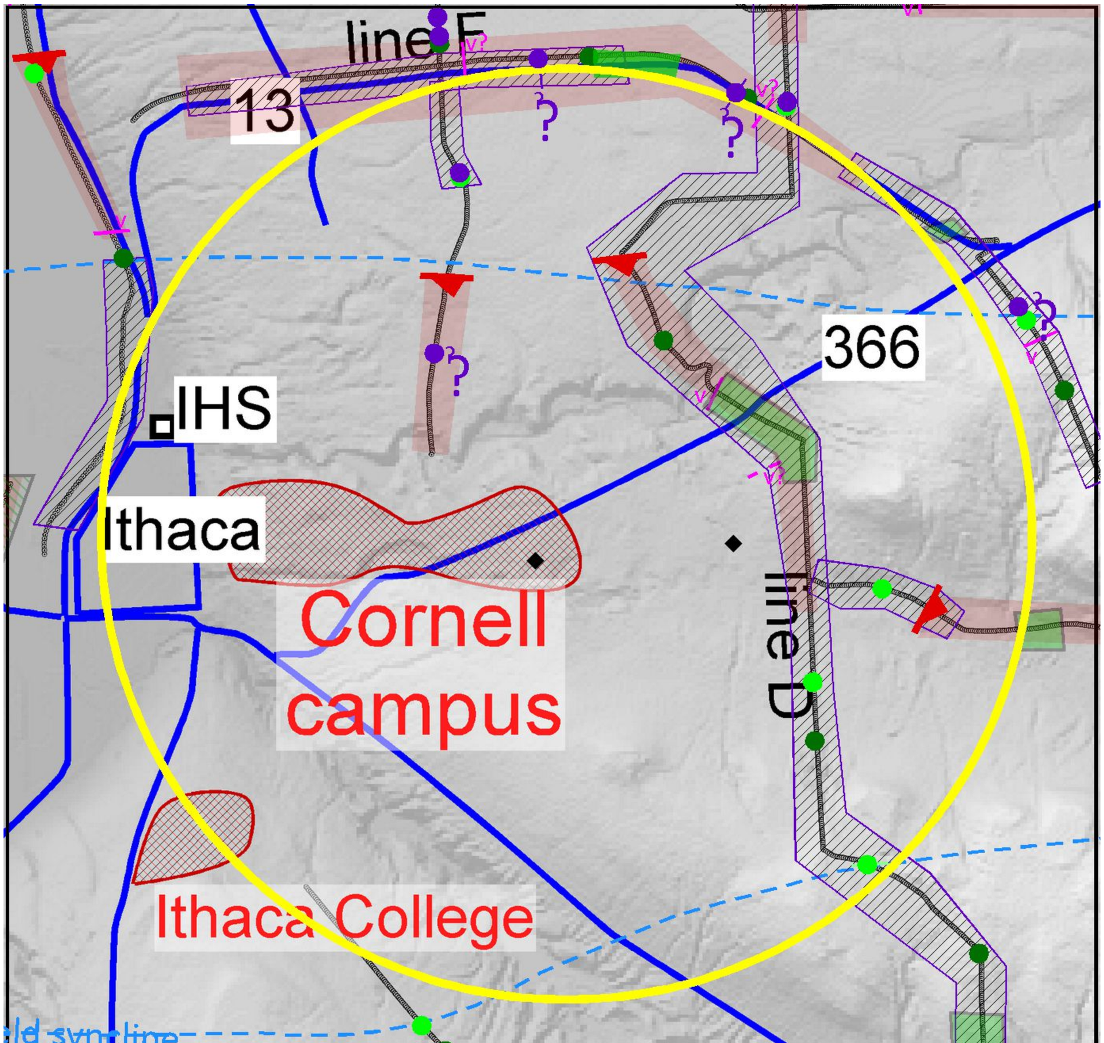


Figure 17. Green polygons mark zones that correspond to plausible positions for a hypothetical steeply dipping fault in the basement (see Figure 9B, C) that would control a fold of the Galway, Potsdam, and contact to basement. If the folds are controlled by a thrust fault (Figure 9D, E, F), then there is no evidence for a basement fault within these green zones. Note that some zones also contain TBR faults, which may mechanically control the fold forms. Three classes of certainty that a fold exists are designated by the colors of the polygons, based on the quality of data (see legend). The dark green polygons north of Cornell are based on more certain data; the intermediate green polygons east and south of campus are based on lower certainty data; the pale cross-hatch polygons west of Ithaca indicate that the fold form interpretation is highly uncertain. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

6.2. Features identified in the subsurface near east campus sites considered for ESH pilot borehole



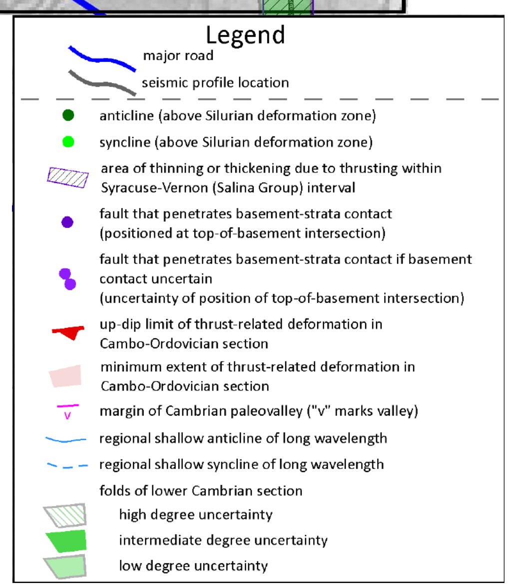


Figure 18. Distribution of structural features in the subsurface within 4 km (2.5 miles) distance of the east end of the Cornell campus. Black diamonds mark two sites under evaluation for ESH test borehole. Polygons: purple cross-hatch marks thrust zones in Silurian Syracuse and Vernon formations; pale red marks thrust zones in Cambrian-Ordovician Galway, Tribes Hill, Little Falls formations, with barbed red lines at the up-dip end of where a thrust cuts upward across a reflector; pale green zones are zones of uncertainty in which a basement fault may exist (for one of two alternative hypotheses to explain folds near basement contact). Green dots mark fold axes in shallow sedimentary rocks. Purple dots mark positions where TBR faults intersect the top of basement. Pink lines mark margins of Potsdam paleo-valleys ("v" on valley side of line). Lengthy blue dashed line marks trace of a long-wavelength synclinal fold axis. Whereas seismic data provide good coverage of the eastern and northern quadrants, the western and southern data controls are slightly beyond the circle with 8-km (5-mile) diameter.

6.2.1. Sedimentary rocks and potential reservoirs

The sedimentary rock framework can be confidently extrapolated across areas between seismic profiles, because there is little variation in the reflection patterns among the seismic lines. Sedimentary rocks that underlie the Cornell campus region have reflection properties similar to the reflection properties near deep boreholes whose well logs and physical cutting samples reveal the vertical succession of rock types (Fig. 3). Although the sedimentary layers imaged in reflection seismic data near campus have been assigned unit names that roughly approximate the formation names used by geologists throughout central New York, only the upper contacts of the Onondaga Formation, Lockport Dolomite, and Trenton Limestone have physical property changes that are highly likely to correspond to easily identifiable individual seismic reflections.

Whereas the vertical scale of the native data environment used for this study is sonic two-way travel time (TWTT), the vertical scale of interest to ESH is depth below surface. To date, the only available conversion of seismic time sections to depth sections is via a model based on seismic reflection stacking velocities (Brown and May, 2019). These contacts above the Onondaga, Lockport and Trenton formations are used to anchor a comparison of a depth-converted seismic profile to depths documented in deep boreholes (Fig. 19). This exercise demonstrates that the stacking velocity model may be roughly correct in the shallow subsurface (to about 5000 ft [1500 m]) (Fig. 19A), but it is highly uncertain at greater depths and appears to systematically overestimate the depth to the top of crystalline basement.

A

B

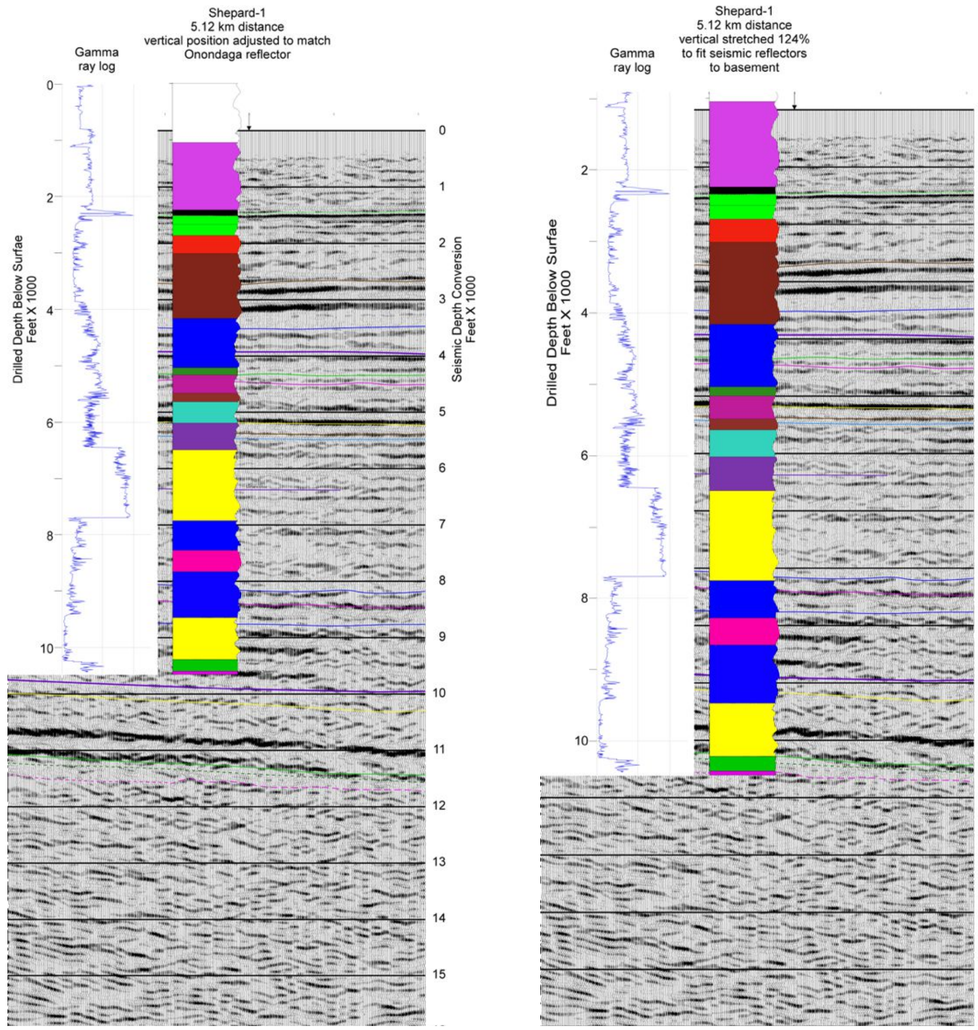


Figure 19. Comparison of a depth-converted seismic profile at the location among the available seismic profiles that is closest to the Danby Shepard-1 well (5.12 km distant). Depth conversions are based on seismic stacking velocities (Brown and May, 2019). A) The borehole vertical distance and depth-converted seismic section are each displayed on their independent scales (depths in feet). Whereas a good match of tops of color-coded units to same-colored reflections is achieved for the borehole units and reflections in the top 5000 ft (1500 m), at greater depths the match fails. Note that the true depth to the Potsdam – crystalline basement contact (green polygon – basal pink polygon) appears to be nearly 2000 ft (600 m) less than the seismic depth interpretation (pink dashed line). B) A 124% vertical stretch of the borehole geological profile produces a match of the top of Onondaga, top of Trenton, and basement to the seismic depth interpretation. This implies that there is a very high degree of uncertainty on depths provided through the existing model of seismic reflection depths. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.

Camp and Jordan (2016) documented the potential that dolomite in the upper part of the Black River Formation may have suitable properties to circulate geothermal water for an ESH project, if the rock is within a short distance to a fault of the TBR set. Nevertheless, the available seismic profiles reveal no TBR prospects near the eastern part of Cornell's campus (Fig. 16). Suitable reservoirs may be associated with TBR faults to the north, near the Ithaca airport, and to the south near Brooktondale (Fig. 14)

Al Aswad (2019) is completing an analysis of the opportunities for suitable natural geothermal reservoir properties in the sedimentary units spanning the Tribes Hill to Potsdam Formations. Her study is based on New York state databases and reports with lithological information coupled to sparse porosity and permeability data (some key wells are located in Fig. 1). Intervals of greatest potential occur within the Galway Formation and in the lower member of the Potsdam Formation (Ausable member). The Galway is widespread in the region below and near Cornell's campus. Although in some sectors of the grid of seismic profiles there is strong evidence that paleo-valleys are filled with sedimentary materials beneath the widespread Potsdam upper member (Table 1), for the seismic lines close to campus the distribution of the Potsdam lower member is highly uncertain (Fig. 20). The current interpretation is that this unit is present under much of the northern quadrant and eastern zone of the 5-mile diameter circle of immediate interest (Fig. 21). Nevertheless, it is not well imaged in the seismic data closest to campus (Fig. 20).

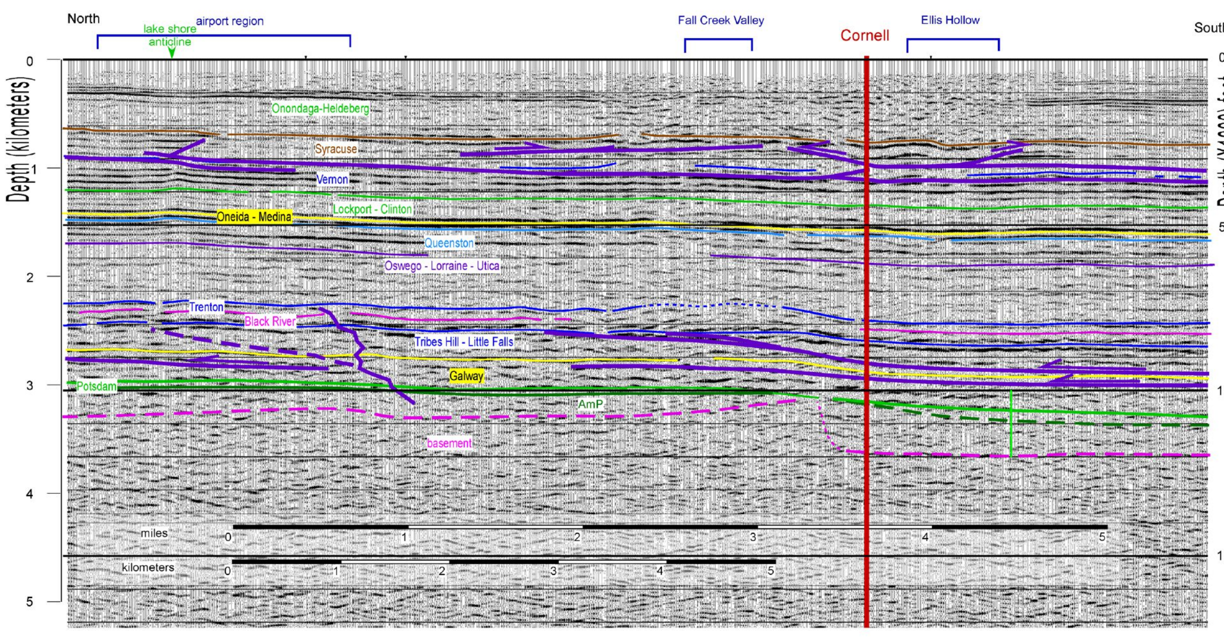
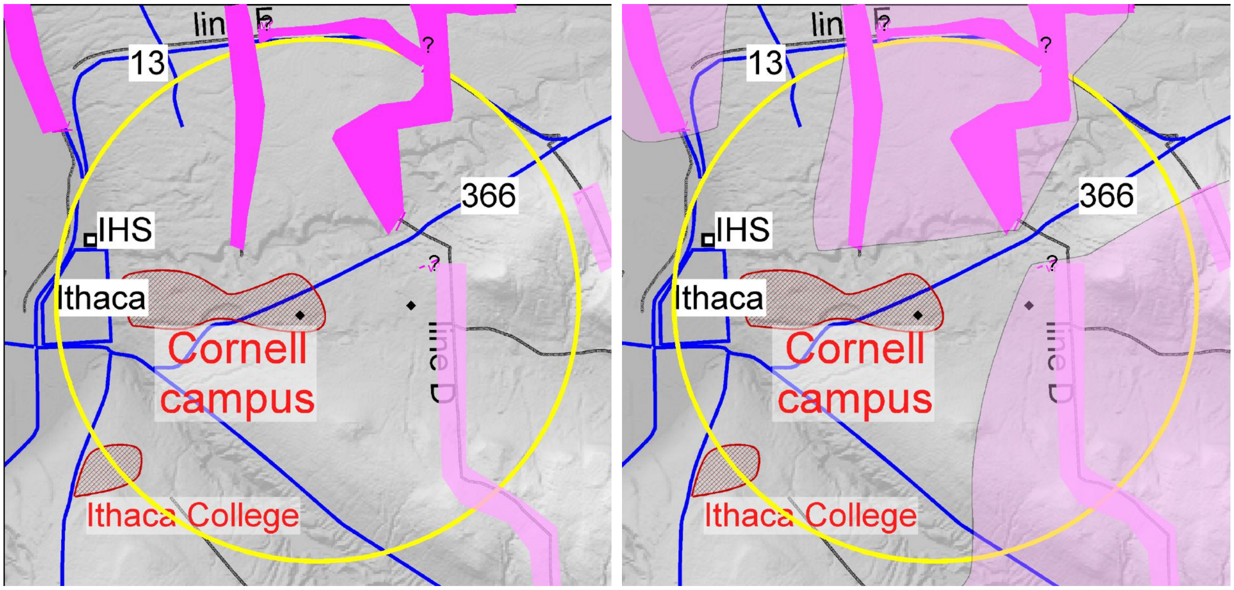


Figure 20. Seismic profile D that passes near the eastern limit of the Cornell campus, displayed with the same vertical and horizontal scales, based on a depth conversion model that likely overestimates depth to basement. The seismic expression of the top of basement is ambiguous, expressed in a dashed pink line. The location of Cornell is shown by vertical red line. The interval between the dashed pink top-of-basement and next overlying mapped reflector (dark green), may be the lower member of the Potsdam (AmP). Whereas this display implies that the thickness of the Ausable member may be as great as 1400 ft (400 m), it also may be not present at all. Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University.



A B

Figure 21. Zoom of Figure 12 shows the distribution of interpreted paleo-valleys at the contact between underlying crystalline basement and the Potsdam Formation. A) Observed spatial limits of paleo-valleys; note that question marks indicate an uncertain interpretation. Dark pink is more certain than medium pink. B) A non-unique interpretation of the extent of paleo-valleys, represented by pale pink polygons. Black diamonds mark two sites under evaluation for ESH test borehole.

6.2.2. Deformation features: folds, thrust faults sub-parallel to the sedimentary layers, and steeply dipping faults

Deformation features cannot be confidently extrapolated across areas between seismic profiles, because the seismic profiles reveal that several categories of features are narrow and irregularly distributed. Within the area of interest (yellow circle, Fig. 18 and figures that follow), for the areas west and south of Cornell's campus there is a lack of 2007 seismic data, and the lower quality 1984 data exist only for the extreme western perimeter. Within the southwest quadrant of the yellow-circled area, no information exists about the presence or absence of structural features. This does not mean that no structural features exist.

Structural categories 1 and 2: A borehole located anywhere near the eastern margin of Cornell's campus is expected to cross a thick interval of disturbed strata (Syracuse, Vernon) between subsurface depths 2500-4000 ft (750-1200 m) (Fig. 22). Folds above this shallow zone of deformation occur with approximately kilometer-spacing and amplitudes less than 20 m. Although the two-dimensional seismic profiles cannot indicate the orientations of these folds (Fig. 22), a simplistic interpretation that their axial traces are parallel the set of longer wavelength folds map at the surface (Fig. 13 and 22, pale blue lines), trending east to east-northeast, is supported by the fact that these folds are more frequently seen on the portions of seismic lines collected along north-trending roadways than along east-trending roadways (Fig. 13). Prucha's (1968) work near Lansing suggests that within the deformed Syracuse and Vernon units there may be an additional set of small-scale folds with a markedly different orientation of fold axes, but this directional information is not resolved with the industry data set.

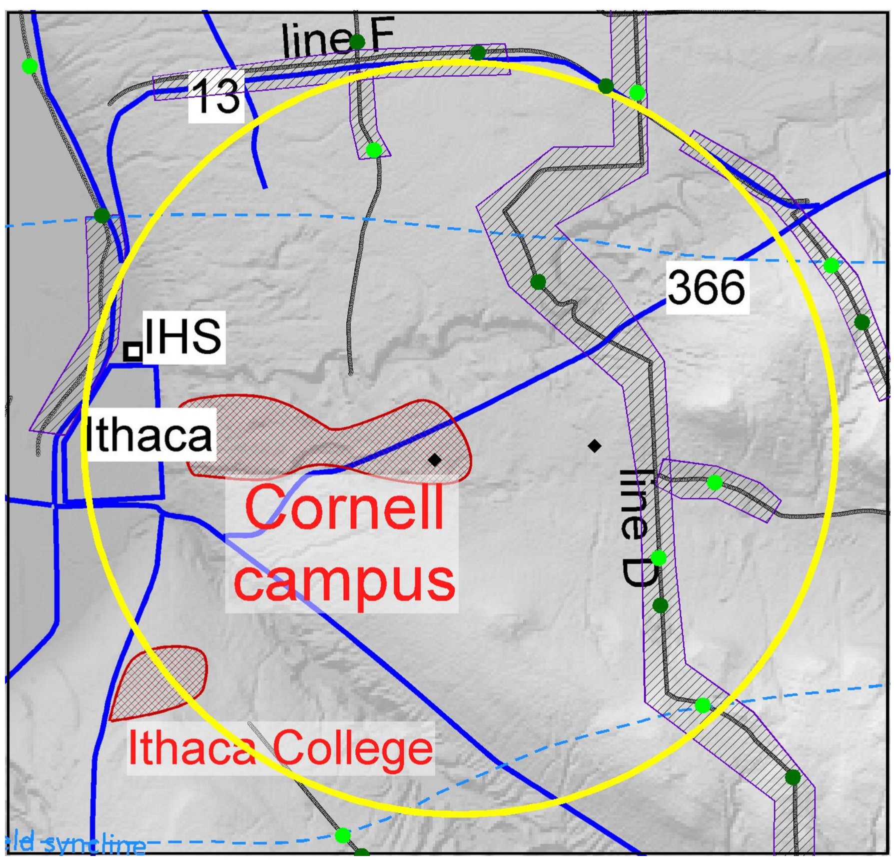


Figure 22. Distribution of folds that approach surface and zones of thrusting and folding within the Syracuse and Vernon Formations. Polygons with cross-hatched fill mark areas of extensive deformation within the Syracuse and Vernon Formations. Dark green dots mark positions of short-wavelength anticlines, and pale green dots mark positions of short-wavelength synclines. The blue lines mark long-wavelength synclines that can be traced across a broader region. Black diamonds mark two sites under evaluation for ESH test borehole.

Structural category 3: Within the area of interest (yellow circle, Fig. 23), there occur few TBR steep faults that disrupt deep strata (Galway through Trenton Formation) and that can be tracked downward to the basement contact. One fairly confident TBR fault is mapped, near BOCES on Warren Road. Four tentative TBR faults are recognized within or immediately outside of the area of interest, for which a question mark next to the purple mark denotes my uncertainty that the fault interpretation is correct

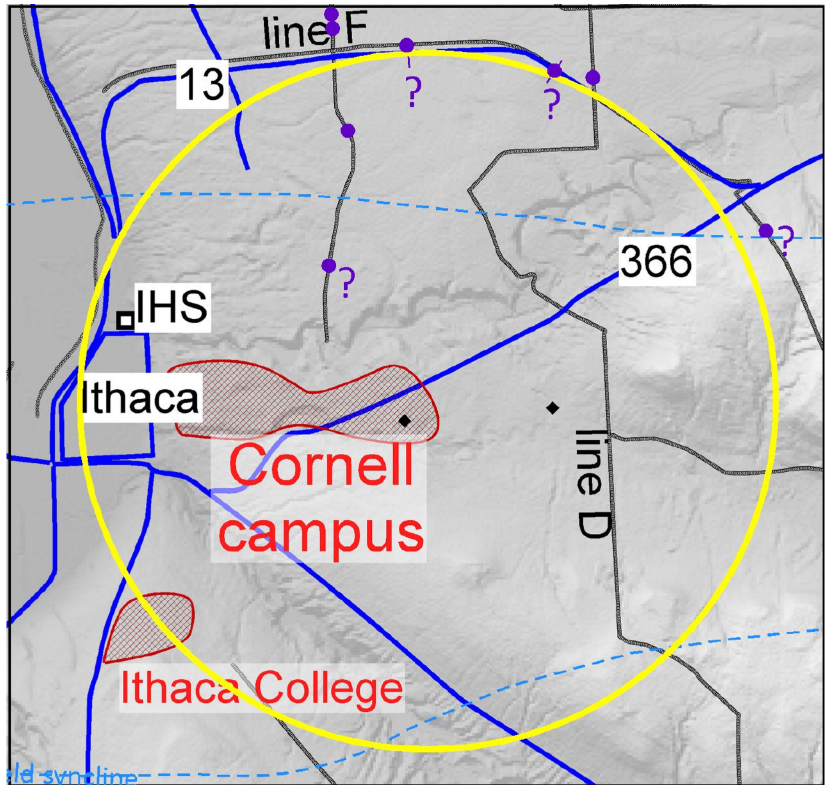


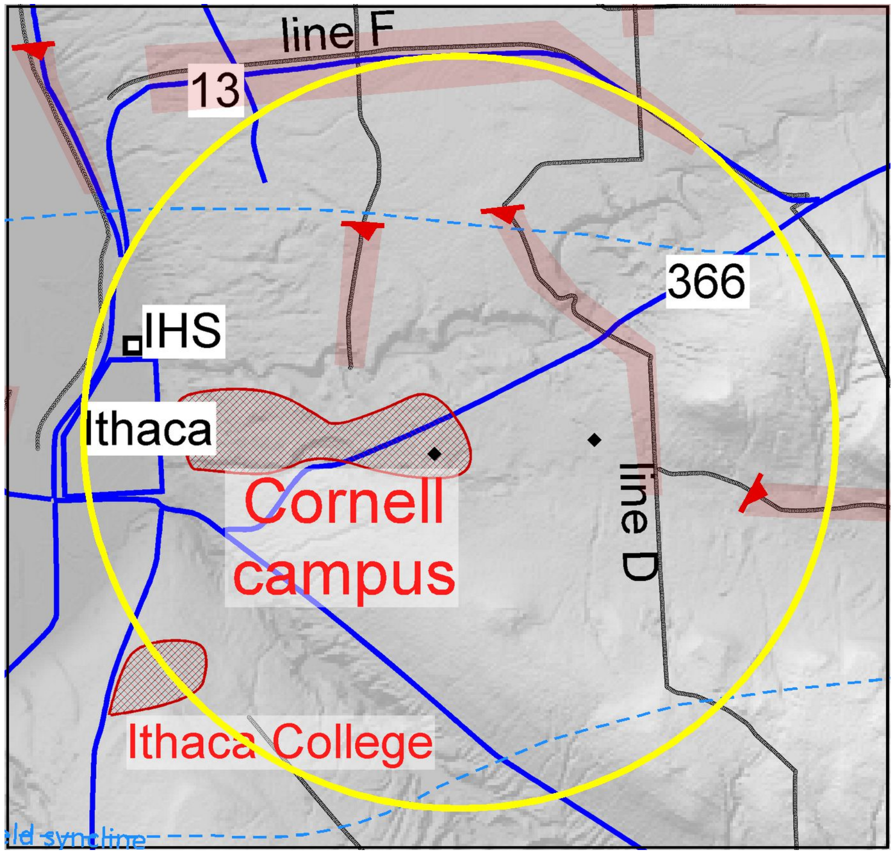
Figure 23. A) Distribution of sub-vertical faults that affect Cambrian and Ordovician strata, with style of Trenton-Black River (TBR) grabens. Locations (purple dots) correspond to position where the imaged fault appears to intersect the top of basement. Question marks indicate uncertainty about the classification of the observed features as sub-vertical faults that intersect the top of basement. Black diamonds mark two sites under evaluation for ESH test borehole.

(Fig. 23). One of these is located approximately 1 km north of Fall Creek near Cornell's golf course, another is located on the north flank of Mount Pleasant, and the others are near route 13 (see profiles C and F, in Supplemental File 2). These locations are all near the northern perimeter of the area of interest, and may indicate the occurrence of one of the TBR grabens.

Structural category 4: A major surprise that emerges from this analysis of recent vintage industry-quality seismic reflection profiles is that there exist thrust faults and fault-bend folds (anticlines and synclines) within the Cambrian-lower Ordovician interval of sedimentary rocks (Table 2; Fig. 24). Were we located in central Pennsylvania, these features would have been expected. However, the continuation of these features approximately 120 km (75 miles) north of the so-called Alleghany Front is news (Fig. 1A). Perhaps the fact that the access by university researchers to a high-quality seismic reflection data set in this region is also highly unusual explains the previous omission of these features.

With reference to an ESH project, this deep thrust deformation is expected to impact the degree of fracturing of the adjacent rocks. The spatial distribution of sub-horizontal zones of fracturing may be mechanically analogous to layers of sedimentary rocks with varying porosity. A general rule is that the width of the zone of fracturing adjacent to a fault increases as the amount of displacement across the fault (or zone of faults) increases (Marrett and Allmendinger, 1990; Fossen, 2016). Near Ithaca, the amount of bedding-parallel displacement across these newly discovered faults is unknown. The geometries of interrupted reflections that are evidence of the thrust deformation (Table 2, category 4) could be analyzed to deduce minimum shortening amounts in the plane of a seismic profile. Until that is done, I am assuming that slip is minor, and may or may not be sufficient to offer improved reservoir properties.

Figure 24. Distribution of bedding-parallel thrust faulting (polygons with pale red fill) within the Cambrian (Galway) and Ordovician (primarily Tribes Hill-Little Falls) interval. Heavy red lines with triangles mark the up-dip limits of steps of thrust sheets across sedimentary units. Blue line marks a long-wavelength syncline known from surface mapping and interpretation of seismic profiles. Black diamonds mark two sites under evaluation for ESH test borehole.



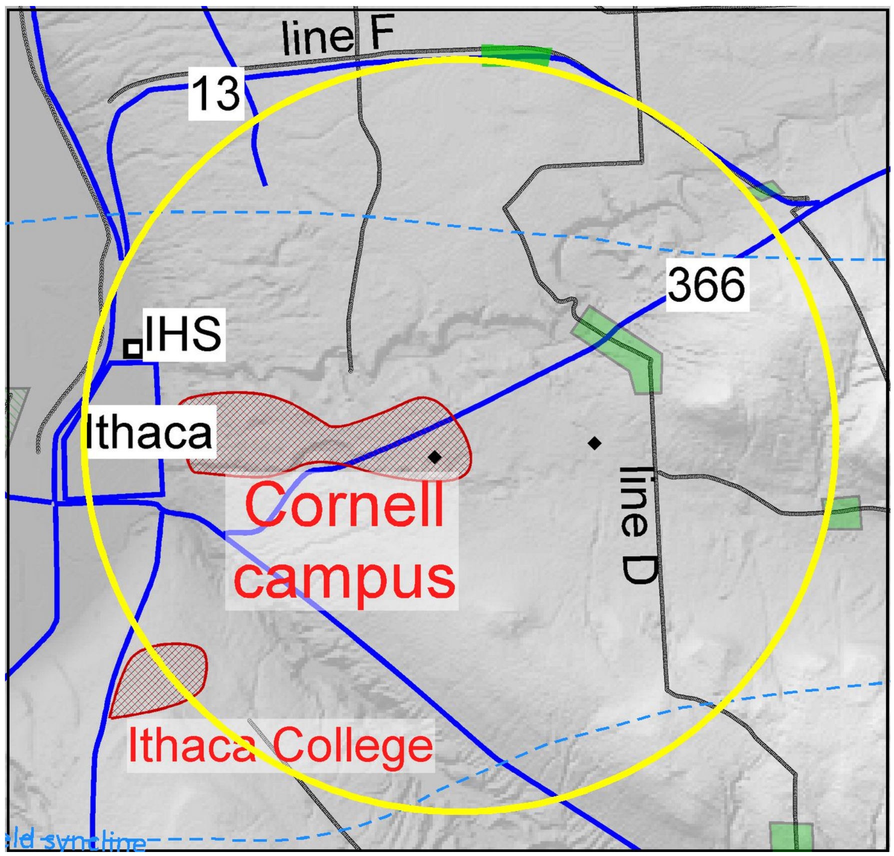
In the 4 km (2.5 mile) radius region encircling the east end of Cornell's developed campus, there is consistent evidence of thrust displacement (Fig. 24). It should be expected that an ESH borehole will cross through a faulted interval. It is likely that several of the deep hydrocarbon exploration boreholes in the region have already bored through faults of this category. However, no one has yet compiled from the borehole records evidence of the nature of rock or fluid properties at those hypothetical thrust horizons.

Structural category 5: The two alternative explanations for broad anticlines and synclines in the Cambrian strata that conform to the basement-sedimentary contact both involve the existence of faults, few of which are not imaged by the seismic data (Fig. 9). For the interpretation that these folds indicate that a steep fault exists in the underlying basement (Fig. 9B, C), there is a related concern that such faults need to be understood relative to the hazard of induced seismicity. For the alternative, that these folds are controlled by sub-horizontal thrust-related structures (Fig. 9D, E, F), the features are interesting and may be useful for ESH reservoir properties.

One example of a basal Cambrian fold form occurs in the seismic profile that skirts the east flank of Cornell's campus, along the western toe of Mount Pleasant (Fig. 25). Figures 9A and 16A uses this location as their example. If the seismically imaged fold form is a physically correct representation of the rocks (and not due to an unresolved complex reflection path), and if the correct explanation is a sub-vertical fault in the basement, then the appropriate area in which to expect either a steep reverse fault (Fig. 9B) or a normal fault (Fig. 9C) is in the green polygon east of campus that traverses Route 366 near Varna (Fig. 24). This zone is about 1.6 km (1 mile) northeast of the Palm Drive Teaching Dairy Barn.

Nevertheless, the existence of widespread thrust faults in the overlying interval of sedimentary rocks leads to the caution that the thrust-fault explanation of these basal Cambrian folds (Fig. 9D, E, F) is equally likely.

Figure 25. Green polygons mark zones that correspond to plausible positions for a hypothetical steeply dipping fault in the basement (see Figure 9B, C) that controls a fold of the Galway, Potsdam, and contact to basement. If the folds are controlled by a thrust fault (Figure 9D, E, F), then there is no evidence for a basement fault within these green zones. The interpretation that a fold exists in the deepest sedimentary rock is of lower confidence (greater uncertainty) for the pale green polygons east of campus than for the darker green polygon along the northern perimeter. Black diamonds mark two sites under evaluation for ESH test borehole.



7. Key Findings and Recommendations

No seismic reflection images for Tompkins County were available publicly prior to this study. Consequently, the analysis presented is a major advance in documentation of subsurface features near Cornell University's Ithaca campus. The method is well suited to identifying features in the layered sedimentary rocks of the upper 3000 m (10,000 ft), but it provides little clear information about the basement rocks beneath.

Sedimentary units with possible interest as geothermal reservoirs are expected within the lowest 300-600 m (1000 to 2000 ft) of sedimentary rocks near Cornell.

Five categories of structural deformation exist, two of which were not expected based on publicly available reports for Tompkins and neighboring counties. Among the expected types of faults, clusters of sub-vertical faults known as "Trenton-Black River" (TBR) structures occur in some sectors of Tompkins County. However, no cluster of these faults is expected within the area near the eastern margin of the Cornell campus.

Not expected was the discovery that a widespread set of sub-horizontal thrust faults deforms the Cambrian and Ordovician sedimentary rocks. Rocks in which these faults are most common are expected to be about 350 m (1150 ft) thick at Cornell's campus. The depth at which these thrusts may be found in a pilot well near the eastern limit of campus is quite uncertain, perhaps as shallow as 2.1 km (6900 ft) or as deep as 3.0 km (10,000 ft).

Of greater uncertainty is the interpretation that the deepest-imaged sedimentary units are folded in some localized sectors; this observation applies to a small fraction of the distance imaged by the 2007 seismic profiles. It is uncertain whether these apparent fold forms are physically real features of the sedimentary rocks. Conventional wisdom holds that two markedly different types of faults could be related to deep folds: near-vertical faults that offset rocks in the basement, or sub-horizontal thrust faults within the poorly imaged deeper sedimentary rocks or at the sedimentary rock-basement contact. If the possibility that all the apparent folds in the higher quality 2007 data are physically valid is considered, and the interpretation that each fold is controlled by a sub-vertical basement fault is explored, then within the Tompkins County-wide 2007 seismic reflection data, 12 zones of average length 0.9 km are designated as plausible segments in which one such suspect deep fault may occur. Those dozen zones comprise 13% of the profiled distance, including one located near Varna, about 1.6 km (1 mile) northeast of the Palm Drive teaching dairy barn. There are multiple layers of uncertainty in this result: the imaged features may not be true folds, and such a fold may be controlled by either a sub-vertical fault within basement or by a sub-horizontal fault above the basement. These contrasting interpretations have different implications for analyses of reservoir properties and for risk analyses.

Additional seismological modeling study may be able to reduce the uncertainty on the physical reality of the apparent folds in the deep Cambrian sedimentary rocks. Perhaps synthetic seismic profiles could be modeled for the scenario of data collection across topography like that of the area east and south of Ithaca, and the synthetics compared to the real data sets.

Further analysis of the reflection data might enable the extraction of more information about rock property variations and potential fault zones within the crystalline basement rocks.

Further value can be derived from the borehole sonic velocity logs and density logs by generation of synthetic seismograms. From these, alternative depth-conversion models can be developed that may help reduce the uncertainty on the true depths to reflectors.

Additional analyses of the available seismic reflection profiles should be conducted for the purpose of making minimum estimates of the amounts of displacement across the thrust faults within the Ordovician and upper Cambrian sedimentary rocks.

In light of the interpretation that the immediate surroundings of the east end of the Cornell campus display no faults in the sedimentary rocks that project downward to intersect the basement rocks, there may be little value to collecting a 3D seismic reflection data set. Even though additional faults in the basement may exist, which one would like to include in risk analyses, the seismic reflection method is not well suited to identifying faults in basement.

Potentially, any fault located near the proposed ESH site is a cause for concern regarding the possibility of inducing earthquakes during fluid injection. However, the susceptibility of such a fault to reactivation depends on the orientation of the local stress field and the orientation of the fault itself. This study determines orientation of faults only relative to the horizontal: some faults are sub-horizontal, and others are sub-vertical. Neither the state of stress nor the geographical oriental of faults in Tompkins County can be assessed with the 2D seismic reflection data studied here. Whereas the geographical orientation of local faults within the sedimentary units could be assessed with 3D seismic reflection data (not currently available), the local stress field orientation can only be determined with borehole measurements at a specific site. Drilling of vertical boreholes is common in upstate New York and more than 3,500 already exist in the Finger Lakes area. Little or no earthquake hazard exists due to drilling activity.

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Supplemental File

Collection of Interpreted Seismic Profiles

See accompanying file.

Supplemental File 2

Supporting Report
“Geological evaluation of subsurface features near Ithaca, NY: interpretations of seismic reflection profiles collected by the petroleum industry”

Data Source: SEI
Data-lease contract manager for Cornell University: Matthew Pritchard
Support from: Atkinson Center for a Sustainable Future Venture Fund

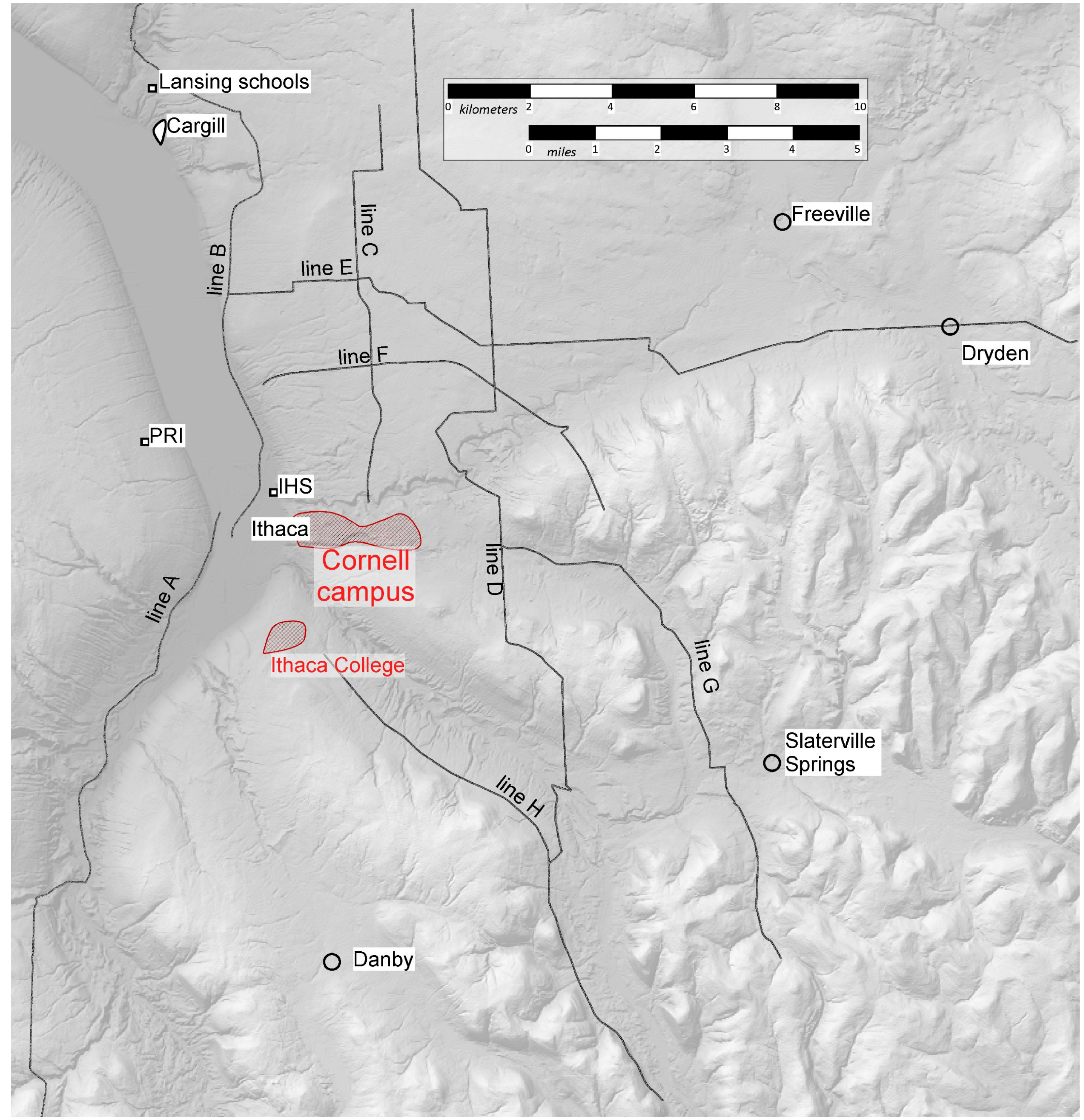
Interpreter: Teresa Jordan

Collection of interpreted seismic profiles

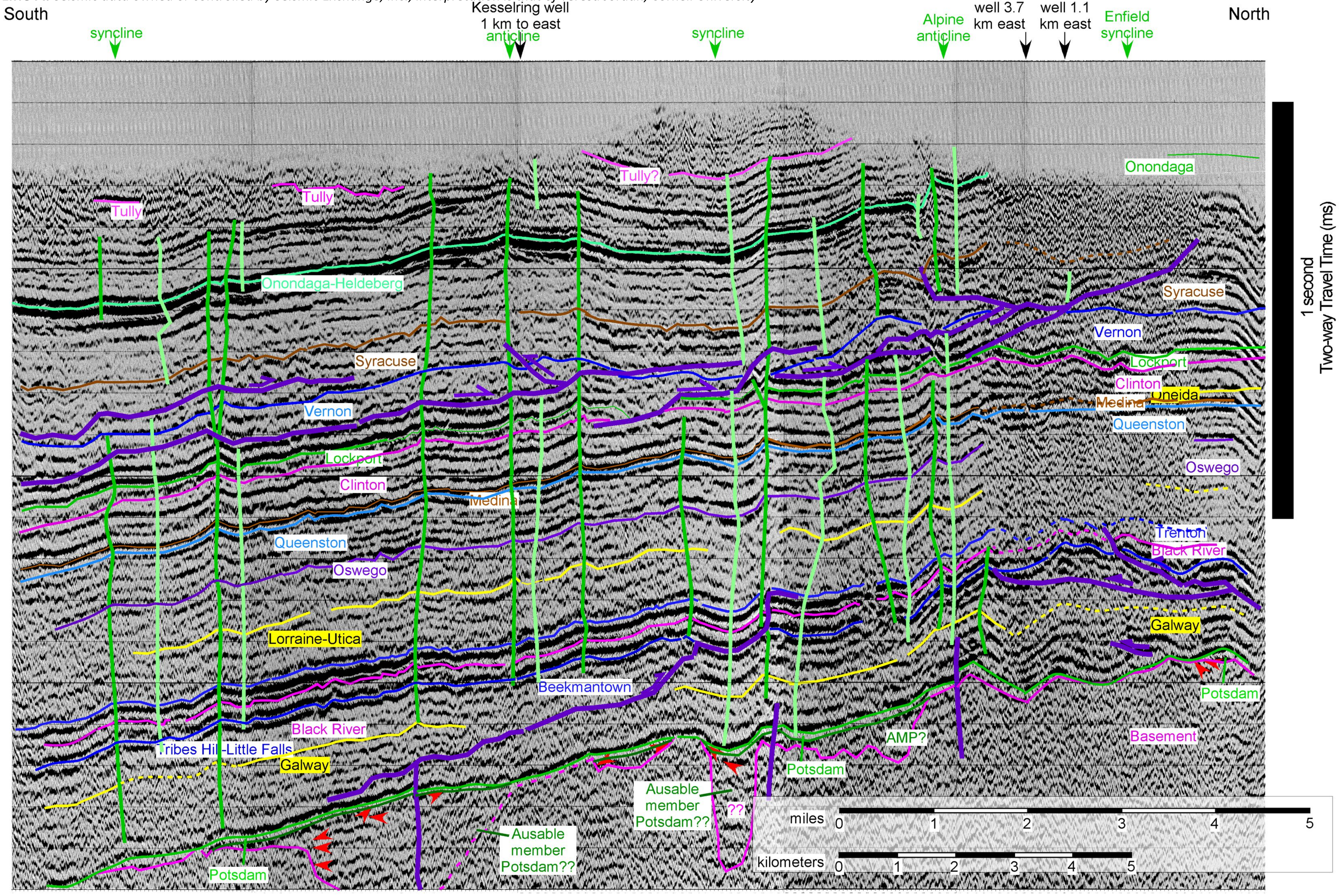
Horizontal axes are distance across the land surface
Vertical axes are Two Way Travel Time

Converting the TWTT vertical scale to approximate depth, based on comparison to the Shepard-1 borehole, the vertical depth scale is exaggerated approximately 2.1 times relative to the horizontal scale.

Locations of seismic reflection profiles. The seismic data are owned or controlled by Seismic Exchange, Inc. Seismic line A extends beyond the southern boundary of this location line. Line B extends beyond the northern boundary of this location map.
See Fig. B of main report.



Line A. *Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University*



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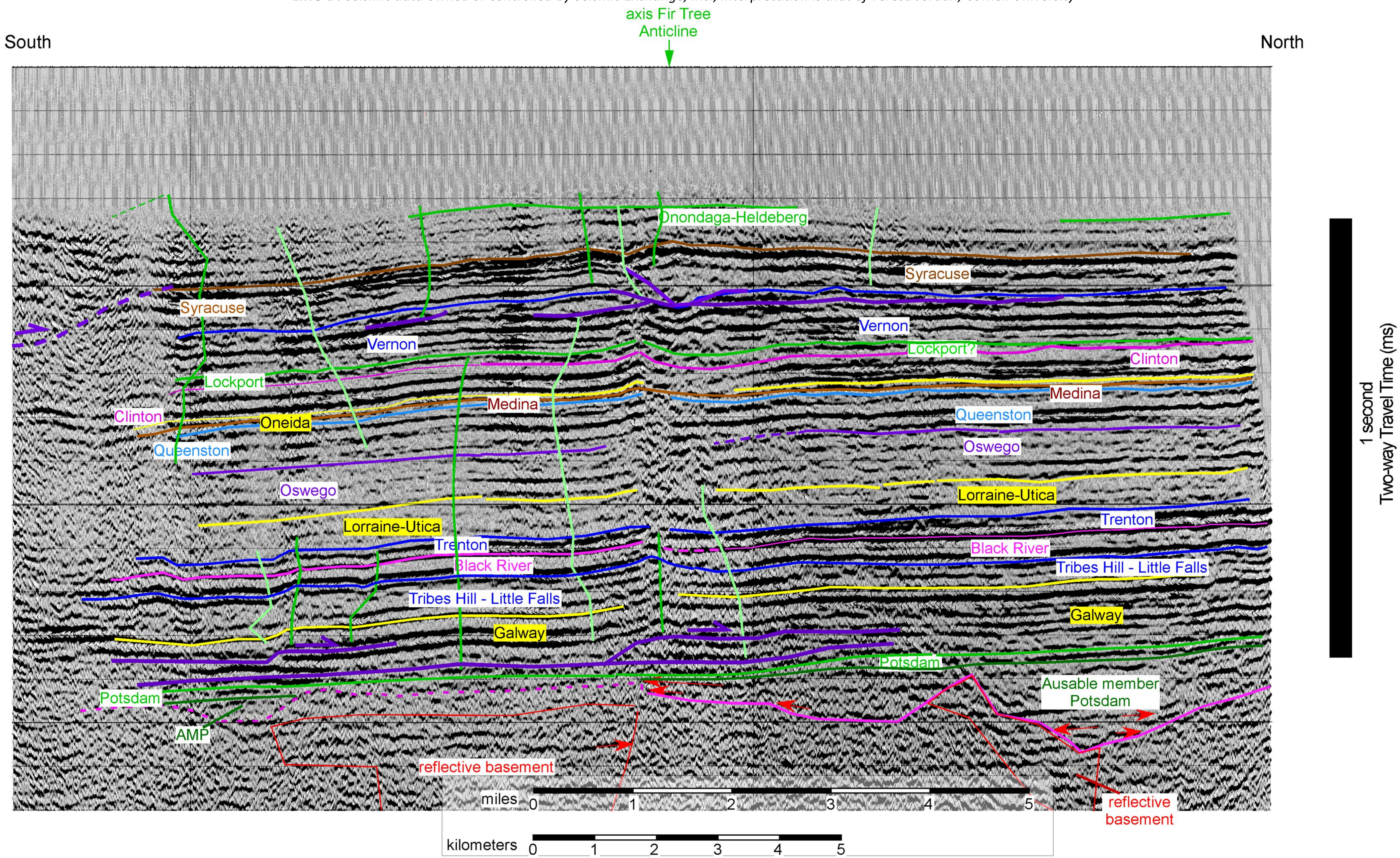

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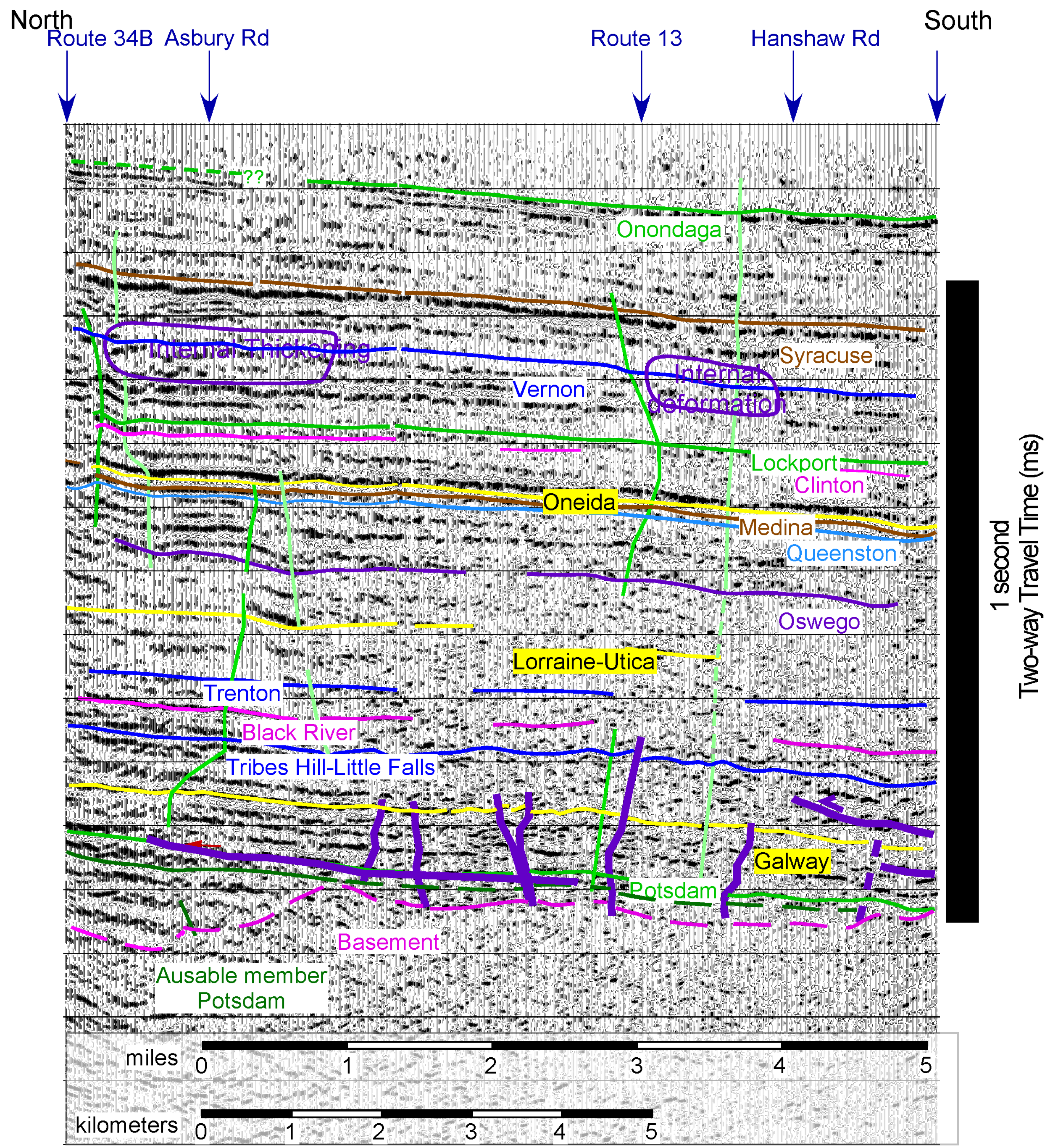

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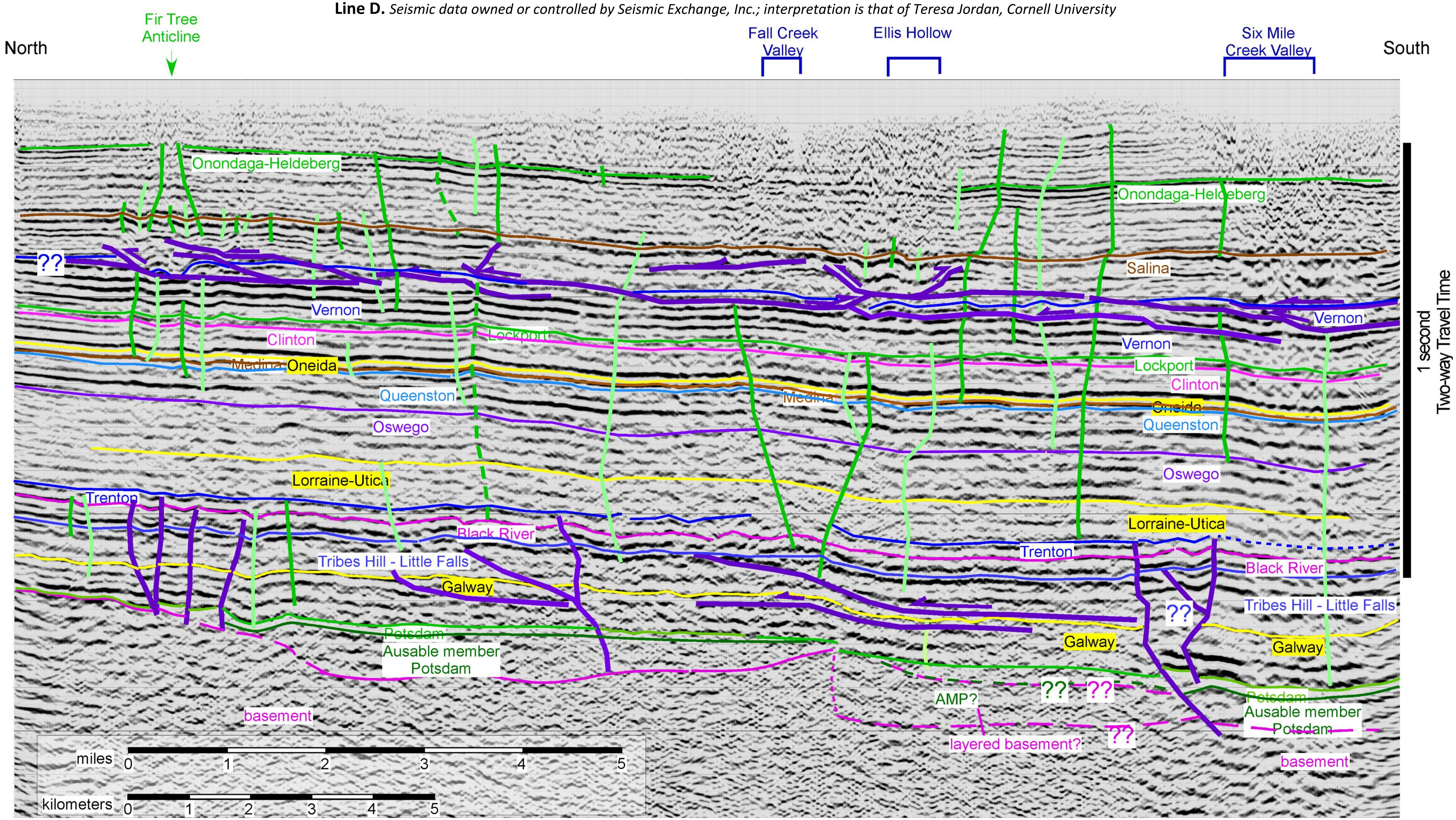

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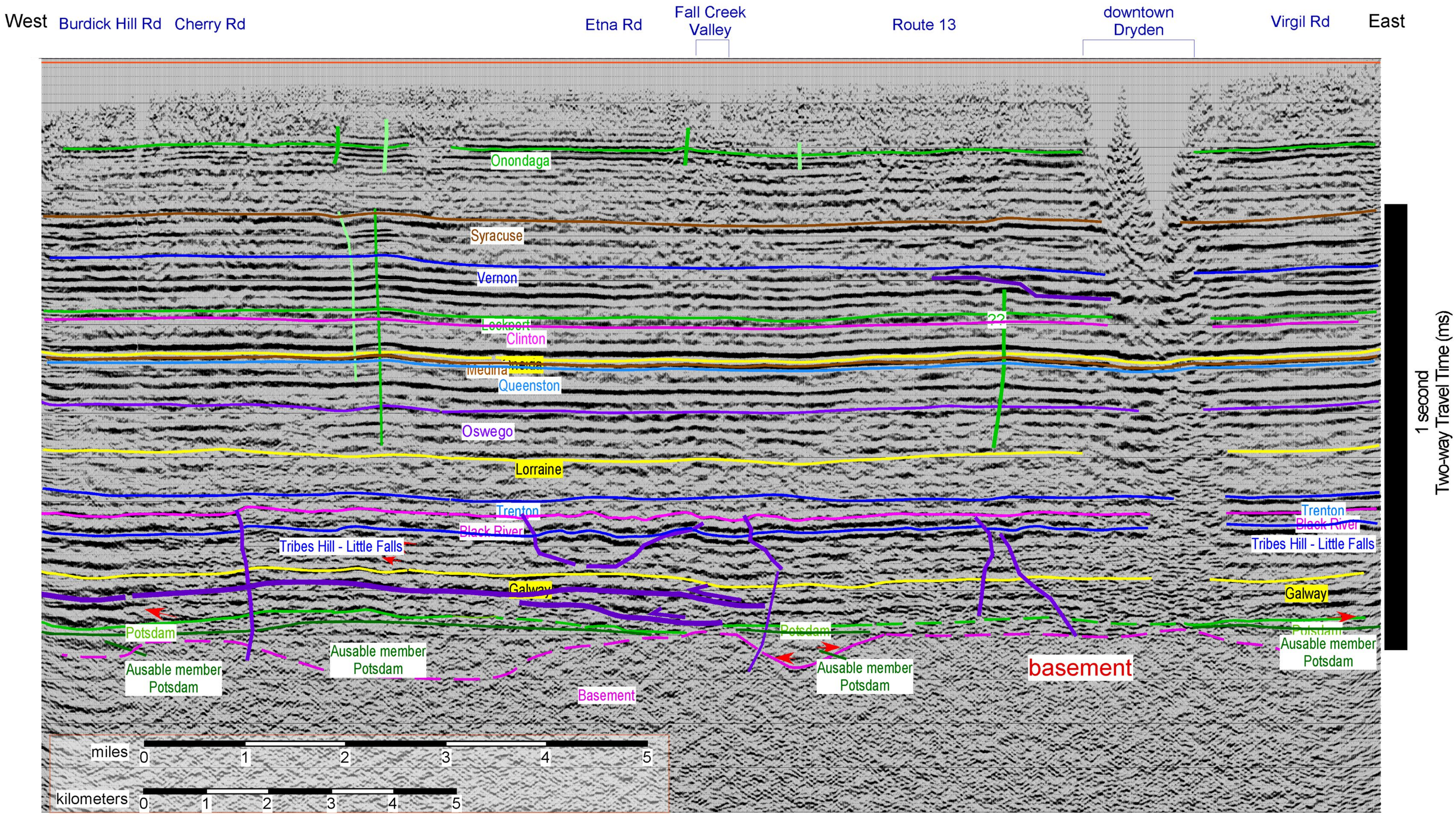

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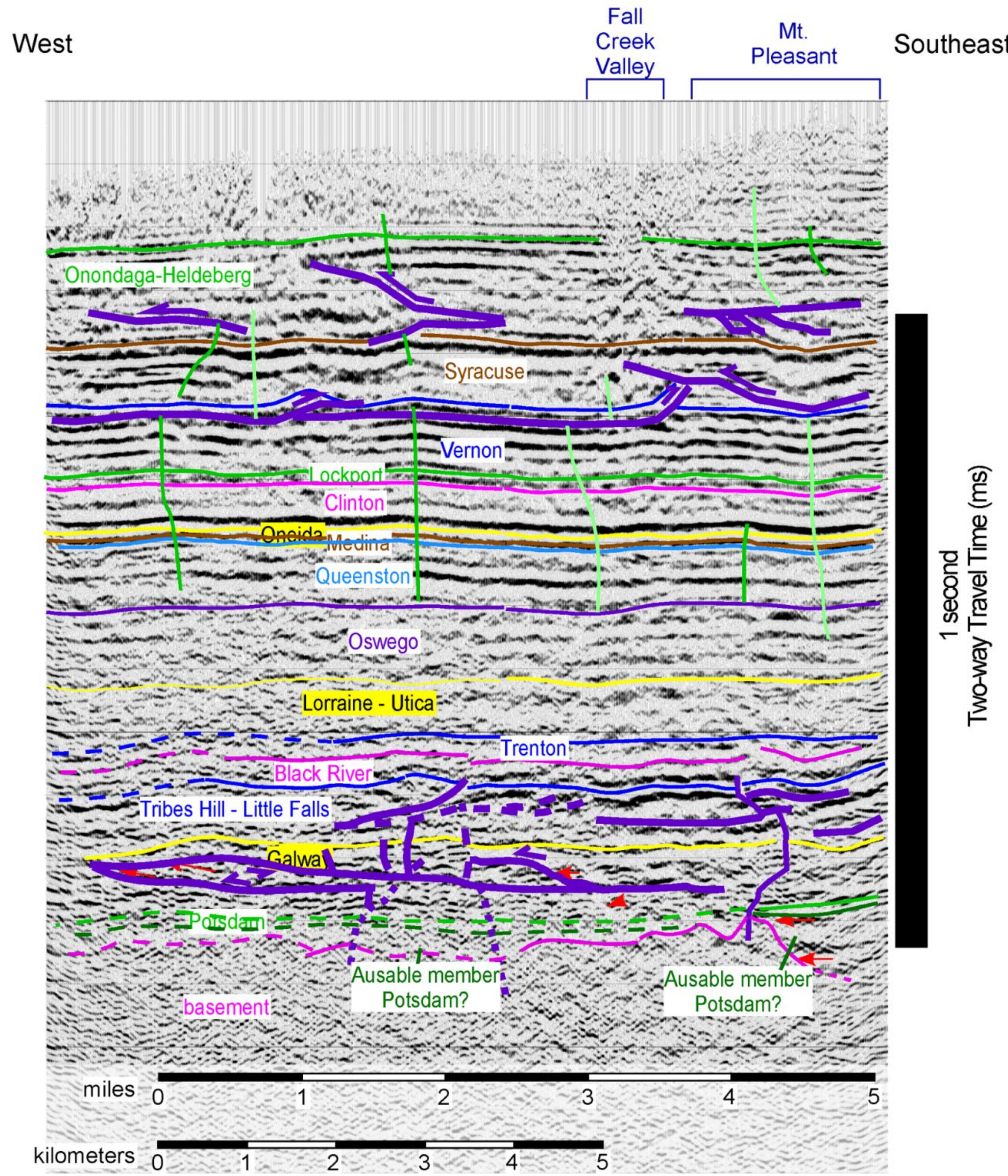

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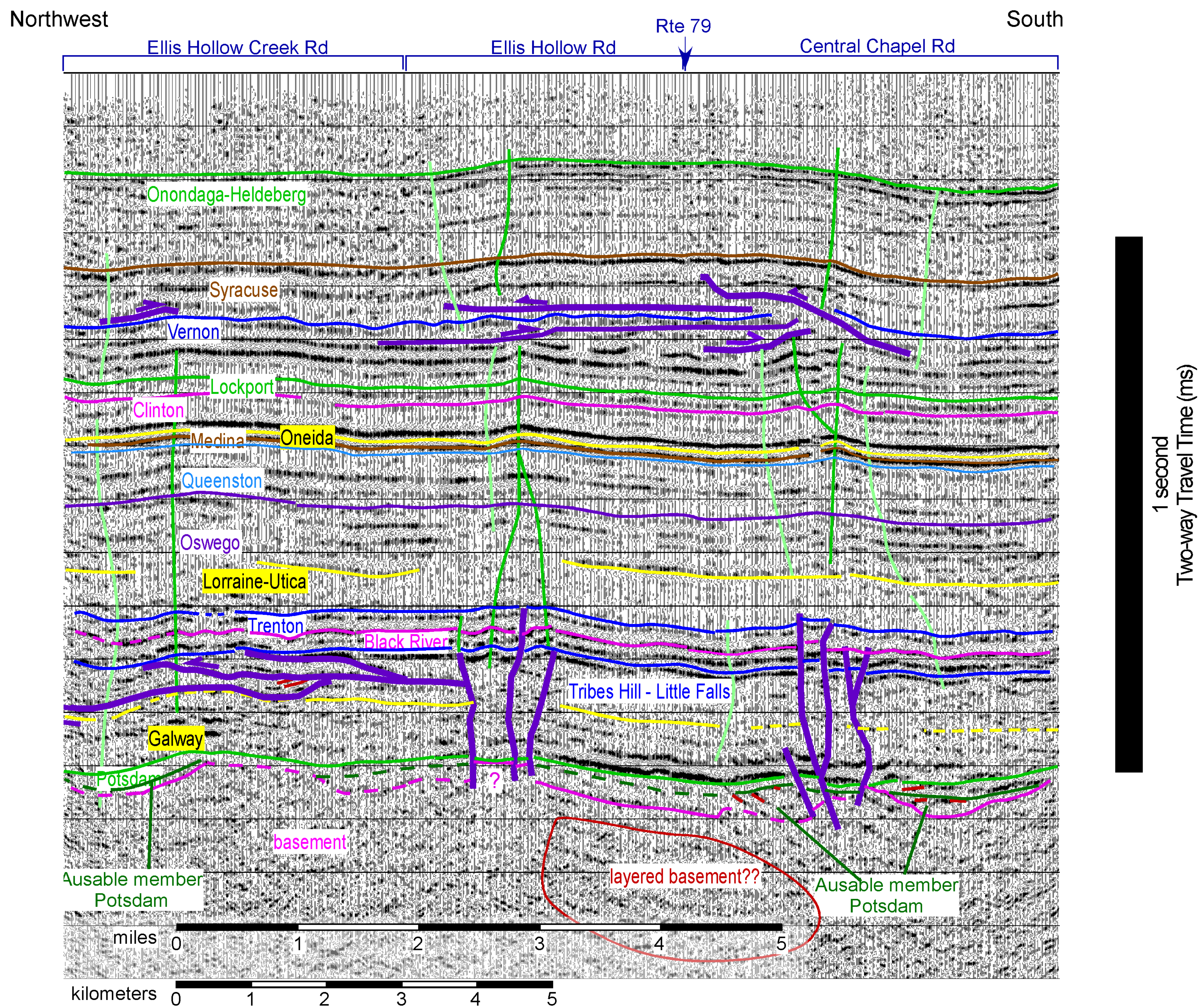

Line H. *Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of Teresa Jordan, Cornell University*